



Fisheries and Oceans  
Canada

Pêches et Océans  
Canada

Science

Sciences

**CSAS**

Canadian Science Advisory Secretariat

Research Document 2009/034

**SCCS**

Secrétariat canadien de consultation scientifique

Document de recherche 2009/034

**Georges Bank 'a' Scallop (*Placopecten magellanicus*) Framework Assessment: Data Inputs and Population Models**

**Cadre d'évaluation du stock de pétoncles « a » du banc Georges (*Placopecten magellanicus*) : Saisie de données et modèles de population**

Ian D. Jonsen, Amy Glass, Brad Hubley and Jessica Sameoto

Population Ecology Division  
Department of Fisheries and Oceans  
Bedford Institute of Oceanography  
P.O. Box 1006, Dartmouth, Nova Scotia B2Y 4A2

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

Research documents are produced in the official language in which they are provided to the Secretariat.

This document is available on the Internet at:

<http://www.dfo-mpo.gc.ca/csas/>

La présente série documente les fondements scientifiques des évaluations des ressources et des écosystèmes aquatiques du Canada. Elle traite des problèmes courants selon les échéanciers dictés. Les documents qu'elle contient ne doivent pas être considérés comme des énoncés définitifs sur les sujets traités, mais plutôt comme des rapports d'étape sur les études en cours.

Les documents de recherche sont publiés dans la langue officielle utilisée dans le manuscrit envoyé au Secrétariat.

Ce document est disponible sur l'Internet à:

ISSN 1499-3848 (Printed / Imprimé)  
ISSN 1919-5044 (Online / En ligne)  
© Her Majesty the Queen in Right of Canada, 2009  
© Sa Majesté la Reine du Chef du Canada, 2009

**Canada**



**Correct citation for this publication:**

**La présente publication doit être citée comme suit :**

Jonsen, I.D., A. Glass, B. Hubley, and J. Sameoto. 2009. Georges Bank 'a' Scallop (*Placopecten magellanicus*) Framework Assessment: Data Inputs and Population Models. DFO Can. Sci. Advis. Sec. Res. Doc. 2009/034. iv + 76 p.

**ABSTRACT**

This research document presents a summary of relevant data inputs and an evaluation of a proposed population model for the assessment of sea scallops (*Placopecten magellanicus*) on the Canadian portion of Georges Bank, zone 'a'. This document was presented as a working paper as part of the advisory process for developing a new assessment framework for Georges Bank 'a' scallops.

Until 2007, the status of the Georges Bank scallop stock has been assessed using a cohort analysis tuned to a commercial catch rate-stratified survey index and a commercial catch per unit effort index. This model suffered both from strong retrospective effects, which resulted in inconsistent estimates of biomass from year to year, and from a lack of recent, reliable aging data, which were used to construct the catch at age matrix. Georges Bank scallops are difficult to age reliably due primarily to the high prevalence of shock marks that are difficult to distinguish from annual growth rings. Consequently, an alternate population model that placed less reliance on aging data was thought to be a more appropriate candidate for assessment of this stock.

A delay-difference population model fit to both the survey and commercial catch rate indices was proposed. This model was implemented in a Bayesian state-space framework, accounting for observation error and process variability separately. Model parameters were estimated using Metropolis-within-Gibbs sampling, a type of Markov chain Monte Carlo sampling method. Scallop growth rates were parameterized from previously published von Bertalanffy growth parameters for the Georges Bank scallop stock. Biomass estimates from this model were compared with estimates from both the cohort analysis and from a surplus production model. These comparisons indicated that the delay-difference model produced biomass estimates that were more consistent with the pattern suggested by both the survey and commercial catch rate indices than did the cohort analysis. Although the biomass trajectories estimated by the delay-difference and surplus production models were similar, the survey catchability estimates from the delay-difference model were more consistent with estimates from the US scallop dredge survey.

Development of a biological reference point was explored in the context of scallop growth rates, natural mortality and exploitation. We show that exploitation rates required for no change in stock biomass can be considered a function of scallop growth rate, discounted for natural mortality. The reference exploitation should then change as the growth rate changes, primarily through changes in average stock size. This approach can be considered precautionary as scallop recruitment to the fishery, which is currently modeled as a log-normal random process, in most years would reduce the realized exploitation level. Posterior distributions of projected biomass under different harvest scenarios, and the associated probabilities of a decrease in biomass, were used to evaluate in-season increases to the interim total allowable catch limit.

## RÉSUMÉ

Ce document de recherche présente un résumé de la saisie de données pertinentes et du modèle proposé d'évaluation du stock de pétoncle (*Placopecten magellanicus*) de la portion canadienne du banc Georges, zone « a ». Ce document a été présenté à titre de document de travail dans le cadre d'un processus consultatif entrepris en vue d'élaborer un nouveau cadre d'évaluation de pétoncle du banc Georges, zone « a ».

Jusqu'en 2007, le stock de pétoncle du banc Georges était évalué par analyse de cohorte axée sur un indice du relevé scientifique par échantillonnage stratifié des taux de prises commerciales et un indice des taux de prises commerciales par unité d'effort. Ce modèle a souffert d'importants effets rétrospectifs qui ont faussé les estimations de la biomasse d'une année à l'autre, et d'un manque de données récentes et fiables de détermination des âges pouvant servir à déterminer la composition du stock selon l'âge. L'âge des populations de pétoncle du banc Georges n'est pas facile à déterminer principalement à cause des marques de choc qui sont difficiles à distinguer des anneaux de croissance annuelle. Par conséquent, pour évaluer ce stock, on croit qu'il serait plus approprié de mettre en place un nouveau modèle d'évaluation de la population qui se fonde moins sur les données portant sur l'âge.

Un modèle d'évaluation de la population de type différence-délai adapté tant au relevé scientifique qu'aux indices des taux de prises commerciales a été proposé. Ce modèle a été utilisé dans un cadre d'évaluation bayésienne de type état-espace distinguant les erreurs d'observation et les variables du processus. Les paramètres du modèle ont été évalués à l'aide d'un algorithme de Metropolis-Gibbs, une sorte d'échantillonnage de type chaîne de Markov à la méthode de Monte-Carlo. Les taux de croissance des pétoncles ont été paramétrés à partir des paramètres de von Bertalanffy antérieurement publiés sur le stock de pétoncle du banc Georges. Les estimations de la biomasse de ce modèle ont été comparées aux estimations de l'analyse de cohorte et au modèle de production excédentaire. Ces comparaisons ont montré que le modèle de type différence-délai, tant d'après l'analyse de cohorte que les indices des taux de prises commerciales, produit des estimations de la biomasse plus justes que les estimations produites par l'analyse de cohorte. Bien que les trajectoires de la biomasse estimées par le modèle de différence-délai et les modèles de production excédentaire étaient similaires, les estimations de la capturabilité produites par le modèle de différence-délai correspondaient davantage aux estimations du sondage sur la drague de pétoncle de la portion américaine.

On a exploré la possibilité d'établir un point de référence biologique dans le contexte du taux de croissance du pétoncle, de la mortalité naturelle et de l'exploitation. Il a été déterminé que les taux d'exploitation n'entraînant aucun changement dans la biomasse du stock de pétoncle sont tributaires du rapport entre le taux de croissance de la biomasse et la mortalité naturelle. Le taux d'exploitation de référence devrait donc changer si le taux de croissance change, notamment la taille du stock moyen. Cette approche doit être considérée avec prudence, car la pêche au pétoncle, qui est actuellement modélisée en tant que processus aléatoire de drague normal, peut produire de faibles estimations d'exploitation pour la plupart des années. On a utilisé une projection postérieure de la biomasse selon différents scénarios de récolte, et les probabilités associées d'une diminution de la biomasse pour évaluer les augmentations saisonnières en fonction de la limite de captures autorisées.



## Introduction

### *Species biology*

The sea scallop, *Placopecten magellanicus*, is found only in the Northwest Atlantic from Cape Hatteras to Labrador and inhabits a variable depth range of about 10-100 m. Scallops are aggregated in patches and harvestable concentrations called beds. The natural extent of these beds is believed to be determined by favourable local conditions, such as water temperature, food availability, and substrate type, as well as spawning and settlement success. Depth also influences growth (Schick et al. 1988; Shumway and Parsons 2006); however, it is likely that depth serves as a proxy for other environmental variables (e.g., temperature, food availability, oxygen, predation, etc.) rather than being a direct explanatory variable.

Sea scallops are sedentary filter feeding bivalves and have separate sexes. In areas that are favourable to growth, they may reach sexual maturity in as early as 2 years. The female gonad is red in colour while the male gonad is creamy white. On Georges Bank, the major spawning period occurs from August to October. Eggs and sperm are released into the water column where external fertilization occurs. Fertilized eggs develop into a larval stage known as a veliger within a few days. Larvae are weak swimmers ( $\text{mm s}^{-1}$ ) relative to the strength of ocean currents ( $\text{cm s}^{-1}$  to  $\text{m s}^{-1}$ ) and can be carried long distances from parental habitats during their time in the water column, which can last 30-60 days. During this period, larvae continue to grow and feed on phytoplankton. Once they reach the pediveliger stage, larvae spend more time near the bottom. Little is known about the settlement process of the sea scallop; however, pediveliger larvae have been shown to delay metamorphosis for up to a month (Culliney 1974) and, therefore, may be able to exhibit some control over substrate selection. Once a settlement location is selected, metamorphosis into a juvenile is believed to be rapid. Juveniles attach themselves to objects such as gravel or shells via byssus threads to anchor themselves and avoid being resuspended into the water column.

Natural mortality of sea scallop is high during its planktonic larval stage. During this stage unfavourable environmental conditions can retard development, currents can sweep larvae away from suitable habitats, and larvae are subject to predation by larger organisms. Once in their adult form, scallops contend with predation from seastars, predatory snails, crustaceans, and some fish species. Unlike many other bivalve species, the sea scallop has the ability to jump or swim. When disturbed, the scallop opens its valves, takes in water, and then expels the water by closing its valves. The water forced out from the corners of the hinge propels the scallop forward. Laboratory studies have demonstrated that swimming bouts rarely last more than 15-20 s or that scallops exceed 1 m above the bottom (Bourne 1964). When undisturbed, scallops rarely swim. This suggests that swimming bouts are used for predator avoidance.

Adult sea scallops are found on a variety of substrate types; however, scallop abundance is higher on gravel than on other sediments types (Thouzeau et al. 1991; Kostylev et al. 2001, 2003). Juvenile scallops are also more highly associated with gravel beds than sandy bottoms suggesting that heterogeneous bottoms, such as gravel beds, may enhance juvenile survival (Thouzeau et al. 1991). In the laboratory, Bourgeois et al. (2006) found crab predation on juvenile sea scallops to be lower on gravel than on sandy bottoms. However, Wong et al. (2006) showed that predation of juvenile sea scallops by crabs and sea stars was not influenced by sediment type. Gravel and pebble may also offer a more stable substrate for

juveniles to attach themselves and avoid being carried away from parental habitats by currents. Juvenile sea scallops have been shown to select heterogeneous sediments (such as pebble and gravel) over homogenous ones (Wong et al. 2006).

The Atlantic sea scallop can commonly reach sizes of 10-15 cm in shell height (the maximum distance between the dorsal (hinge) and ventral margins). Its growth is estimated from the position of external rings on the shell that represent annual intervals. These rings form by a relative slowing or cessation of growth rate, which often occurs in late winter (Stevenson and Dickie 1954; Black et al. 1993). However, rings are also formed when scallops experience trauma, such as from storms or contact with fishing gear, and are referred to as shock rings (Black et al. 1993). If shock rings are not distinguished from annual rings, the age of scallops can be overestimated (MacDonald 1984). Other means of measuring growth include analysing growth rings on the shell hinge ligament, tagging scallops, using size-analysis techniques, and oxygen-isotope ratio analysis.

Scallop growth is highly variable and is dependent on local environmental conditions. Georges Bank is one of the worlds most productive areas for sea scallops and represents some of the fastest growth rates observed for sea scallop stocks (Bourne 1964). Even within the bank; however, growth rates can vary spatially and inter-annually. The size and weight of the meat (the adductor muscle) partly depends on the shell height of the scallop; however, this relationship can vary from place to place within the same area. Changes in meat weight within and between areas are believed to be influenced by season, depth, and temperature.

### ***History of fishery***

The sea scallop is the most economically important bivalve species in North America and has been fished for over 125 years. In Canada, the fishery was initially focused on inshore scallop beds in the Bay of Fundy; however, after World War II, the offshore industry developed with Georges Bank as the primary focus of the Canadian fleet (Naidu and Robert 2006). Georges Bank was fished competitively from the mid 1940s until 1973 when it was transformed into a limited entry fishery that restricted the fishery to 76 Canadian licenses for vessels greater than 19.8 m (65 ft) (Stevens et al. 2008). The offshore fleet currently consists of 2 types of vessels, wetfish vessels that land fresh scallops, and freezer trawlers that have onboard freezing capabilities to land either fresh or frozen scallops. The first freezer trawler was introduced to the offshore fleet in 1991. In 2002, 2 additional freezer trawlers using more advanced technology were added to the existing fleet of 1 freezer trawler and 26 wetfish vessels. The number of wetfish vessels has since declined to 11 with 6 freezer trawlers. The fleet typically fishes two New Bedford style rakes simultaneously, one on each side of the vessel. The rake consists of a heavy metal frame and a bag knit with steel rings, 3 or 4 inches in diameter. Rakes can range in size from 4-6.1 m width.

In 1977, Canada and the US both declared 200-mile fishing zones. This limited Canadian vessels to fishing a disputed zone of Georges Bank. The dispute and the competitive fishery continued in this area until the International Court of Justice (ICJ) established an international boundary in October 1984, which awarded the Northeast portion of Georges Bank to Canada. The establishment of the ICJ line initiated discussions between DFO and industry on how to rebuild and maintain the stock in the future. In 1986, an agreement was made to enter into a trial Enterprise Allocation (EA) program in which the goal was to rebuild the stock

and stabilize future catches by harvesting the resource more effectively. As part of the EA program, management measures were implemented that included legal meat counts, and a total allowable catch (TAC). Also in 1986, the Minister divided the inshore and offshore fleets with a separation at the 43°40' North latitude line near Yarmouth, Nova Scotia. This led to the inshore fleet being phased out of the Georges Bank fishery over the next few years, and the offshore fleet was not permitted to fish in the Bay of Fundy waters.

Since 1986, the offshore scallop fleet has fished Georges Bank year-round under the EA management regime with some modifications to the regulations to reflect advances in the fishery, industry and associated technology. In 1995, the offshore scallop industry and DFO implemented further management measures. A 100% dockside monitoring program was established to monitor catches by the offshore scallop fleet. The industry also initiated a program in which the proportion of the catch less than 10 grams was restricted to 10% by number or 5% by weight. In 1998, the industry started to fund a port sampling program that examined the meat size within the catch. This sampling is conducted on all scallop fishing trips. These measures complimented the regulatory meat count that was already in place as part of the management program to help the fishery target larger animals and increase yield.

Further management action was taken in 1998 with the implementation of a fleet wide satellite vessel monitoring system for tracking vessel activity and the division of Georges Bank into two management zones. Zone 'a' is the traditional scallop fishing grounds and is a more productive area than zone 'b' which is considered to be marginal scallop habitat (Figure 1). The separation of Georges Bank allowed the opportunistic exploitation of the marginal scallop area (zone 'b') when strong year classes occurred. Management for zone 'a' included a TAC and a meat count of 33 meats per 500 g. Zone 'b' was managed with a rolling TAC and a meat count of 50 meats per 500 g. In 2008, the rolling TAC approach was abandoned in favour of a single TAC for zone 'b'.

Advancements in the management of the offshore scallop stocks on Georges Bank have continued. In 2005, the offshore scallop industry established the first voluntary juvenile scallop closure. This action protects high densities of juvenile scallops from fishing mortality allowing them to grow to commercial size. The first seed box was implemented until January 1st, 2007 and three new voluntary closure areas were implemented in 2008.

## **Fishery Data**

Data from commercial fishery logbooks include spatially and temporally referenced catch and effort and are used to calculate the total landings and catch per unit effort (CPUE) index of commercial size biomass. A single position was reported in the logbooks for each day of fishing. Logbook data were available from 1955; however, a number of issues affect the quality of the data (to a greater degree in earlier years). The time series used for input into the assessment model begins in 1981 making some of the issues more manageable. Prior to the creation of the ICJ line in 1984, American scallop boats were landing scallops from the Canadian side of Georges Bank but these landings were not reported in the offshore logbooks. Also, prior to 1986 Canadian inshore fishing boats fished Georges Bank and their catch was not recorded in the offshore logbooks. In general, logbooks were incomplete prior to 1994 because some catch was reported by sales slip only. These issues have been

accounted for and adjustments have been made to the total landings from Georges Bank prior to 1994 (G. Robert, *pers. comm.*). Since the 1998 division of Georges Bank into zones 'a' and 'b', landings and effort have been reported separately for Georges Bank 'a' and 'b' (Table 1). In order to calculate total landings for the Georges Bank 'a' prior to the 1998 division, the proportion of the Georges Bank landings with a recorded position that could be attributed to Georges Bank 'a' was multiplied by the total landings to estimate landings on Georges Bank 'a'.

### **Catch and effort**

Catch rates were previously reported in kilograms of scallop meats per hours fished (kg/h) or in kilograms of scallop meats per the number of crew x hours fished x width of gear in metres (kg/crhm) (Robert et al. 2000). In order to compare the catch rates from both freezer trawlers and wet fish vessels an attempt was made to standardize their catch rates in kilograms of scallop meats per hours fished x width of gear in metres (kg/hm). The analysis indicated that when catch rate is expressed as kg/hm a standardization coefficient is not necessary to combine the fleets (generalized linear model with factors: fleet, year, month; P for fleet < 0.001; conversion factor = 1.02). Hereafter, catch rates are reported in kg/hm units.

The CPUE index  $U$  was calculated using a jackknife estimator (Smith 1980) on class 1 data from the commercial logbooks. Class 1 data are the daily logbook records that include prorated catch (kg), effort (hm) and position (lon, lat). The jackknife estimator for  $U$  is:

$$U_{-j} = n \left( \frac{C}{E} \right) - (n-1)R_{-j} \quad (1)$$

where,  $n$  is the number of records in a given year,  $C$  and  $E$  are the sum of the total yearly class 1 catch and effort, respectively, and  $R_{-j} = \left( \frac{\sum C_{ij}}{\sum E_{ij}} \right)$  with the  $j$ th observation removed. The value of the CPUE index for a given year ( $U_i$ ) is the average of all  $U_{-j}$  for that year.

Catch rates declined in the early 1980s followed by a rapid increase and decline and then a period of more gradual increases and decline to the mid 1990's when effort declined sharply (Figure 2). Catch rates spiked in 2000-2002 due to two large cohorts recruiting to the fishery, landings increased to some of the highest since implementation of Enterprise Allocation and effort was near the lowest for the entire period (Figure 2). The 2007 catch rate and effort are based only on data outside of a voluntary seedbox that was opened at the start of the 2007 fishing season.

### **Catch sampling**

Information on meat weight composition of the commercial landings (port sampling data) was collected prior to 1981, but, in order to match with the survey time series (see below), only data from 1981 to present are used for assessment purposes. Samples have been collected through a dockside monitoring program since 1995 with 100% of landings sampled. Prior to 1995, samples were obtained from the fishing vessels by DFO personnel and less than 100% of landings were sampled.

Catch samples were reported at a 10 minute square resolution prior to 2001 and at a 1 minute square resolution from 2001 onward. Prior to 1998, samples in each 10 minute square west of the dividing line between zones 'a' and 'b' were used to estimate catch composition for Georges Bank 'a' (Figure 1). From 1998 onward, samples were recorded separately for Georges Bank 'a' and 'b'.

Distinct phases of the fishery are evident in the monthly and annual average meat weights (Table 2, Figure 3). From 1981 to 1985, smaller meats were landed (10-14 g) than in 1986-1995 (15-20 g) or 1996-2007 (16-25 g). The landed meat weights tend to peak in June and July but maxima have occurred between February and September (Table 2).

## **Survey Data**

### ***Survey design***

Scallop dredge surveys have been conducted in August on Georges Bank prior to 1981 but coverage of the bank was limited and highly variable. Since 1981, surveys have covered the important commercial scallop beds in most years (Figure 4). The survey vessels have changed 3 times since 1981. From 1981 to 1993, the survey was conducted on board the DFO research vessel E.E. Prince. From 1994 to present, the survey has been conducted on board commercial scallop vessels; 1994-2006 FV Cape Keltic, 2007 FV E.E. Pierce, and 2008 FV Tenacity. In all years, the survey gear used was a single 2.44 m New Bedford style scallop dredge with a 38 mm polypropylene liner. No comparative towing data are available to determine if fishing characteristics differ between consecutively used vessels, but the constancy of the survey gear and commercial vessel captain, Ross Hartman, should help mitigate any differences.

The survey on Georges Bank employs a commercial catch rate stratified sampling design (Robert and Jamieson 1986), where catch rate strata are defined annually. This design likely tracks abundance of commercial sized scallops well; however, strata are not fixed among years and coverage is dictated by the distribution of fishing activity within a relatively short period (the September to June preceding the survey). Additionally, the efficiency of the survey design relative to a simple random design was shown to be marginal for the stratification and, in years prior to 1995, much poorer for the allocation scheme (Smith and Robert 1998). Since 1995, survey tows have been allocated proportional to strata area (Robert et al. 2000), yielding an allocation efficiency equivalent to a simple random design.

### ***Reconstruction of survey strata***

A reconstruction of the original survey strata was necessary because the areas occupied by the strata were not retained for most previous years. These areas are required to calculate survey stratified means and standard errors. The reconstruction was accomplished using fishery logbook data for the period 1981-2007.

In the past the catch rates were reported in kg/crhm units for all fishing boats prior to the introduction of freezer trawlers and only for the wet fish fleet afterwards. As part of the process for designing the survey in 2008, an attempt was made to incorporate both fleets by



standardizing their catch rates. The standardization analysis indicated that, when the catch rate units were kg/hm, a standardization coefficient was not necessary to combine the fleets (generalized linear model with factors: fleet, year, month;  $p_{\text{fleet}} < 0.001$ ; conversion factor = 1.02). Therefore, in reconstruction of the original design, kg/hm was used as the catch rate unit and assume that once dredge width and tow time are taken into account, the two fleets have the same fishing power. A linear model was fit to catch rates in kg/crhm versus catch rates in kg/hm in order to convert strata boundaries in kg/crhm (0.2, 0.5, 1, 2) (Robert et al. 2000) to kg/hm (4, 9, 18, 36) (Table 3).

In order to define the strata, catch rates were contoured for each year of the survey. Fishery data from September to June preceding the August survey were used in the contouring. The consequences of time-integrated versus instantaneous data are that one would expect a greater degree of variation between points sharing the same spatial position. For example, it would be quite likely that two vessels fishing the same place at different times in the season would have different catch rates. These differences could be driven by growth, recruitment, fishing or natural mortality. To compensate for this temporal variation, catch rates were smoothed spatially by dividing the bank into a grid of 1 minute of latitude ( $3.43 \text{ km}^2$ ) cells and either: (1) the mean of all reported catch rates within each cell was calculated or (2) catch rates were estimated using the jackknife estimator (Equation 1). For the purposes of assigning strata, catch rates were considered to be zero in cases where there were no data available for a particular cell. The resulting smoothed data were then interpolated using a bilinear spline interpolation (Akima 1978) over a grid of 0.01 degrees of latitude ( $1.23 \text{ km}^2$ ) and plotted using the converted strata boundaries to define the strata 1 through 5.

Using the two different catch rate estimators, strata areas were calculated and the original survey tows (Figure 4) were post-stratified based on the reconstructed strata for each year. Areas were calculated in standard towable units ( $1950.72 \text{ m}^2$ ), yielding 634 per 0.01 degree of latitude ( $1.23 \text{ km}^2$ ) cell. Therefore, the number of towable units in each stratum is equal to the number of cells belonging to each stratum times 634 (Table 4). Survey tows were post-stratified by the catch rate class of the 0.01 degree cell that was occupied by the mid-point of each tow.

The two catch rate estimators yield slightly different catch rate contours; the jackknife estimator suggests lower catch rates overall (compare Figure 5 and Figure 6). Both of these approaches under-estimate the original catch rate contours estimated for the 1999 survey year from Robert et al. (2000) (Figure 7) and across all survey years when strata id's of all tows are compared (Figure 8, Figure 9). For example, tows that originally belonged to stratum 4 were more likely to be post-stratified into strata 1-3 (Figure 9). The contouring of commercial catch for September to June in 1998-1999 (Figure 10) matches very closely with the Robert et al. (2000)'s contouring of commercial catch rates for the same time period (Figure 7), suggesting that commercial catch rather than catch rate was used to define survey strata for the 1999 survey. It is uncertain if catch rather than catch rate was used to define survey strata in other years. It would make little sense to define strata using commercial catch alone because fishing effort is not taken into account. Therefore, despite the apparent bias in the estimation of catch rate contours and in the subsequent post-stratification of survey tows, we chose to use the jackknife estimator approach. In practice, neither the mean catch rate nor the jackknife estimator methods yield stratified survey means that are substantially different from the simple means. Uncertainty in the survey point estimates cannot

be evaluated relative to original values as these were rarely reported.

### Size composition and growth

Shell height frequencies for the survey series (1981-2007) are presented in Figure 10 to Figure 11. The survey provides quantitative information on numbers of scallops  $\geq 40$  mm but only provides an indicative measure for smaller individuals. For example, strong year classes are typically first observed in the survey at 30-40 mm (age 2), but note the cohort in the 10-20 mm size range in 2007 (Figure 10). The exceptionally strong 1996 year class was first clearly observed in 1998 and recruited to the fishery in 2000-2001 (Figure 11).

Contemporary aging data are not available for the Georges Bank Scallop stock. Difficulties in distinguishing annual rings from shock rings make aging unusually challenging compared to other scallop stocks. A range of von Bertalanffy parameter estimates exists from the 1960s to the mid 1980s (Naidu and Robert 2006) (Table 1).

The parameters from Brown et al. (1972) (Table 1) were used in previous stock assessments for Georges Bank scallops (Robert et al. 2000) and are used here to predict shell height at age, convert the shell height at age into a weight at age via an allometric relationship between meat weight  $w$  and shell height  $h$ ,

$$w = Ah^B \quad (2)$$

where  $A$  and  $B$  are parameters to be estimated. This relationship can be linearized by taking logs of both sides and fit as a linear mixed effects model to account for scallops sampled within a given year  $t$  having more similar meat weight - shell height relationships than those between years,

$$\log(w_{it}) = \log(A + a_t) + (B + b_t) \log(h_{it}) + \epsilon_{it} \quad (3)$$

where  $w_{it}$  is the meat weight of the  $i$ th scallop in year  $t$ ,  $A$  and  $B$  are the fixed effects parameters describing the among-year meat weight - shell height relationship,  $a_t$  and  $b_t$  are the random effects parameters describing the within-year relationships and  $\epsilon_{it}$  are the error terms.

This approach has the advantage of borrowing strength from data collected across multiple years to estimate within-year relationships when sampling across the full range of recruit and fully-recruited scallops was not achieved. More complex models, accounting for extra variability between samples and autocorrelation among years, could be fit but these are unlikely to influence the scaling parameters considerably.

The mixed effects model (Equation 3) was fit to hydration sample data (summarized in Table 1, Figure 12) from the August survey on Georges Bank 'a' (Figure 13). Hydration samples were collected from at least one tow made within each 10 minute square on Georges Bank in each year from 1982 to present.



The random effects parameters suggest relatively little between-year variability in the meat weight to shell height relationship (Table 9). Below average meat weights were observed in 1984, 1996 and 2005, and above average meat weights were observed in 1986 and 2000. All other years were similar to the average (compare red versus blue lines in Figure 14). Consequently, we use the fixed effects parameters to convert shell height at age predicted by the von Bertalanffy growth rate from Brown et al. (1972) into weight at age (Figure 15). The slope,  $p$ , of the regression in Figure 15 corresponds to the Ford growth parameter.

### ***Size at recruitment to fishery***

The size at recruitment to the fishery is assumed to be knife-edged (see *Delay difference model*); that is all scallops above the initial size at recruitment experience the same fishing mortality. Port sampling data provides the information to understand how size at recruitment may have changed since 1981. We first convert meat weight samples to shell heights using information from the hydration data (Table 8, Table 9). In addition to the hydration data collected during the August survey, samples were collected in May from 12 monitoring stations. Hydration samples were also collected from commercial fishing trips to Georges Bank during the period 1982 to 2006. The samples from commercial trips; however, neither cover all months in all years, nor cover the bank as consistently as samples from the August survey (54% of samples are from August). Therefore, we chose to use only the data from the August survey at the expense of some error in the conversions as landings occur throughout the year.

Examination of the port sampling data revealed 3 distinct phases in which size at recruitment to the fishery differed. From 1981 to 1985, at least 95% of landings were of scallops > 75 mm shell height. This increased to > 85 mm from 1986 to 1995 and to > 95 mm from 1996 to 2007 (Figure 16). Consequently, we allowed the knife-edged recruitment to differ between these three periods, and scale survey numbers and biomass indices accordingly.

### ***Survey numbers and biomass***

Shell height frequencies were divided into three size classes based on size at recruitment to the fishery. Fully-recruited scallops are individuals that are fully-recruited to the commercial gear. Recruits are scallops that will recruit to the fishery within one year. Pre-recruits are scallops that will recruit to the fishery in more than one year.

Trends are presented as stratified mean numbers and biomass scaled to the fishable area of Georges Bank 'a', assuming both a constant size at recruitment of 95 mm and the 3-phase size at recruitment described previously. The 3-phase size at recruitment is used to fit the delay-difference population model (see *Delay difference model*). Survey biomass indices were constructed using information from the annual shell height - meat weight relationships (Table 9) to convert annual numbers at height to biomass (g) at height. Conversions were made for each survey tow and a stratified mean biomass was calculated for commercial and recruit size scallops.

### *Constant size at recruitment*

The survey numbers suggest four phases of rapid increase in numbers of fully-recruited scallops (> 95 mm) due to large recruiting cohorts in 1985-86, 1992 and 1999-00, and variable rates of decline as these cohorts were fished out (Figure 17 A). A similar pattern is evident in the biomass index, although commercial biomass (> 95 mm) prior to 2000 was half to one-third of that observed in 2000-2003 (Figure 18 A). Prior to 1995, the large recruit cohorts do not appear to occur one year before a correspondingly large increase in fully-recruited numbers, suggesting a blurring of size classes vulnerable to fishing consistent with the port sampling data (Figure 16). The recruit size cohort observed in 2006 did not result in an increase in fully-recruited scallops in 2007. Recruitment is highly variable with large pulses occurring roughly every 5 to 7 years between 1981 and 2007.

### *Variable size at recruitment*

The assumption of 3-phases to size at recruitment yields different patterns in survey numbers and biomass for fully-recruited scallops in years prior to 1996 (Figure 17 B, Figure 18 B). Numbers of fully-recruited scallops were considerably greater in 1986 and 1992 compared to those from the constant size at recruitment index (Figure 17 A). A similar pattern is evident in the survey biomass indices (Figure 18). The difference in fully-recruited biomass estimates (prior to 1996) between the two size at recruitment assumptions is less for biomass than for numbers. This difference is consistent with the pattern of average meat weight of fully-recruited scallops from both the survey and commercial samples; lower than average meat weights are evident in earlier years (Figure 15).

## **Population Models**

### ***Delay-difference model***

The delay-difference model is a biomass dynamic model that was first proposed by Deriso (1980) and generalized by Schnute (1985). Unlike simpler Surplus production models (Schaefer 1954; Pella and Tomlinson 1969), delay-difference models have separate parameters to describe growth, recruitment and mortality, thereby retaining much of the biological realism contained in fully age-structured models. The model is based upon three key assumptions. First, the increase in mean body size with age has the following linear relationship,

$$w_a = \alpha + \rho w_{a-1} \quad (4)$$

where  $w_a$  is weight at age  $a$  and  $\alpha$  and  $\rho$  are parameters to be estimated. Second, selection to the fishery is knife-edged, that is, all ages  $k$  and older have equal probability of being caught. Third, all fully-selected individuals experience the same natural mortality rate.

Delay-difference models are flexible with different forms accommodating varying degrees of available information (see Meyer and Millar 1999a; Quinn and Deriso 1999; Smith and Lundy 2002a,b, for several examples). The following version was proposed by Hilborn and Walters (1992),

$$B_t = \left[ \exp(-M) \left( \rho + \frac{\alpha}{\bar{\omega}_{t-1}} \right) (B_{t-1} - C_{t-1}) + \omega_k R'_t \right] \quad (5)$$

where  $B_t$  is biomass at time  $t$ ,  $M$  is the instantaneous rate of natural mortality,  $C_{t-1}$  is the observed annual catch,  $R'_t$  is the number of recruits here assumed to be stochastic, and  $\rho$  and  $\alpha$  are growth parameters estimated via Equation 4. The variables  $\bar{\omega}_{t-1}$  and  $\omega_k$  represent the average weight of fully-recruited and recruiting scallops, respectively. The growth term  $\rho + \alpha/\bar{\omega}_{t-1}$  represents the growth potential of the stock, taking into account stock size structure via  $\bar{\omega}_{t-1}$ . The growth potential is greatest when the the stock is young and average meat weight is small; growth potential declines asymptotically to 1 (no growth) as the stock ages and average meat weights increase (Figure 20 A). For example, commercial biomass increases due to growth were approximately 25% over the last 8 years, but much higher in the early 1980's (Figure 20 B) when average meat weights were much smaller (Figure 19).

We use a Bayesian state-space approach to estimating the states  $B_t$  and additional parameters from research vessel (RV) survey and commercial catch data, as per Smith and Lundy (2002b,a). This approach was proposed by Meyer and Millar (1999a) because it allows incorporation of random errors in both the dynamics and the observations and because it can handle non-linearity in the dynamics better than other filtering approaches such as the Kalman filter. In the present context, the key feature of state-space models is that they allow an unobservable, stochastic process to be modelled using observations that are made with error. This is a natural fit for fishery time-series problems because the data collected are typically indices (e.g., survey biomass and/or commercial catch rates) of the true state (biomass) of a stock which can not be observed directly. The freely available software WinBUGS (version 1.4.2, Lunn et al. 2000) was used to perform Markov Chain Monte Carlo (MCMC) integration (via Gibbs within Metropolis-Hastings sampling) required to implement the Bayesian state-space filter (see Jonsen et al. 2003, and references therein).

As per Meyer and Millar (1999a), rescaling the  $B_t$ 's by a constant  $K$ ,  $P_t = B_t/K$ , improves convergence of the Gibbs sampler. Therefore, Equation 5 becomes,

$$P_t = \left[ \exp(-M) \left( \rho + \frac{\alpha}{\bar{\omega}_{t-1}} \right) \left( P_{t-1} - \frac{C_{t-1}}{K} \right) + r_t \right] \eta_t \quad (6)$$

where  $r_t = R_t/K$ ,  $R_t = \omega_k R'_t$  and  $\eta_t$  is a log-normal random variable representing the process variability inherent in the dynamics, i.e.,  $\eta_t \sim \text{LN}(0, \sigma_\eta^2)$ . Equation 6 is known as the process or state model and is one of two coupled models that comprise a state-space model. The second model is known as the observation or measurement model which relates the unobserved states  $B_t$  to the observed indices. We consider two indices of fully-recruited biomass, the survey biomass index for fully recruited scallops  $I_{f(t)}$ , the commercial catch rate index  $U_t$ . We also include an observation model to relate unobserved recruiting biomass  $r_t$  to the observed survey biomass index for recruit size scallops  $I_{r(t)}$ . In each case we assume a proportional relationship between the observed index and true fully-recruited or recruiting biomass:

$$I_{f(t)} = q_p P_t K \tau_t \quad (7)$$

and

$$I_{r(t)} = q_p r_t K \epsilon_t \quad (8)$$

where  $q_p$  are the proportionality coefficients for the fishery phases  $p=1,2,3$  (see *Variable size at recruitment*),  $P_t K$  and  $r_t K$  scale biomass back to  $B_t$  and  $R_t$ , respectively, and  $\tau_t$  and  $\epsilon_t$  are log-normal random variables for the observation error in  $I_{f(t)}$  and  $I_{r(t)}$ , respectively, i.e.,  $\tau_t \sim \text{LN}(0, \sigma_\tau^2)$  and  $\epsilon_t \sim \text{LN}(0, \sigma_\epsilon^2)$ .

Similarly,

$$U_t = q_U P_t K \nu_t \quad (9)$$

where  $\nu_t$  is a log-normal random variable for the observation error in  $U_t$ , i.e.,  $\nu_t \sim \text{LN}(0, \sigma_\nu^2)$ , with variance  $\nu^2$ .

### **Prior Distributions**

The Bayesian paradigm allows pre-existing information to be formally incorporated into an analysis by selecting prior distributions for model parameters. The priors reflect both what is known about a particular model parameter and how well that information is known. However, little information on the parameters in the model for sea scallop exists and we resort to using the following priors for  $q_p$ ,  $q_U$ ,  $\sigma_\eta^2$ ,  $\sigma_\tau^2$ ,  $\sigma_\epsilon^2$  and  $\sigma_\nu^2$ ,

$$\begin{aligned} q_p &\sim \text{U}(0, 1) \\ q_U &\sim \text{U}(0, 1) \\ \sigma_\eta^{-2} &\sim \text{gamma}(3, 0.44629) \\ \sigma_\tau^{-2} &\sim \text{gamma}(3, 0.44629) \\ \sigma_\epsilon^{-2} &\sim \text{gamma}(3, 0.44629) \\ \sigma_\nu^{-2} &\sim \text{gamma}(3, 0.669435) \end{aligned}$$

Note, that priors are placed on the precision (1/variance) rather than the variance terms. The inverse gamma priors [gamma(3, 0.44629), gamma(3, 0.669435)] have expected values that correspond to coefficients of variation (CV) of 0.5 and 0.625, respectively (see Smith and Lundy 2002b, for a more detailed explanation). The larger CV implied by the prior on  $\sigma_\nu^{-2}$  was chosen because an initial run suggested that the model fit rather more closely to the CPUE index than to the survey index.

As  $K$  is set to be the population biomass in year 1, we use a mildly informative log-normal prior on  $K$  with 10% and 90% quantiles approximately equal to 4 000 and 20 000, respectively:

$$K \sim \text{LN}(9.21034, 0.5409)$$

Growth parameters,  $\alpha$ ,  $\rho$ ,  $\omega_k$ ,  $\omega_{k-1}$ , were estimated from the research survey data and subsequently held fixed in the state-space models. Natural mortality  $M$  was assumed to be 0.1, which is consistent with past assessments (Robert et al. 1994, 2000).

To fit the delay-difference model, we collected a total of 80 000 samples was generated in each of 2 chains, the first 40 000 samples of each chain were discarded as a burn-in and every tenth sample thereafter was retained to reduce autocorrelation, yielding 8 000 samples from the joint posterior. We selected contrasting values within the range specified by each of the prior distributions to initialize the two chains; these values are given in [Appendix A](#). Convergence was assessed by examining plots of Brooks, Gelman and Rubin convergence statistics and by comparing posterior density plots for the first, middle and last third of the saved iterations for each chain. WinBUGS code, initial values and data for the delay-difference model are provided in [Appendix A](#).

The data used to fit the delay-difference model are the survey biomass indices for fully recruited  $I_f$  and recruit size  $I_r$  scallops, average weight of fully recruited scallops  $\bar{w}_t$ , scaled by number of fully-recruited scallops in the survey, commercial CPUE index  $U$  and commercial catch  $C$  ([Table 10](#)).

## ***Sensitivity analyses***

### ***Growth***

Little contemporary data exist to parameterize the growth term in the delay-difference model. As a consequence, we make use of previously published von Bertalanffy growth parameters (Brown et al. 1972). To understand how biomass estimates and projections may be influenced by different growth rate assumptions, we conducted a sensitivity analysis of the delay-difference model. Because imposing different fixed growth rate assumptions on the model will shift the biomass trajectory up or down but not change the pattern over time, our goal is to better understand the uncertainty in the biomass estimates of the default parameterization of the delay-difference model.

### ***Priors on variances***

We used informative gamma priors on precision terms for the default implementation of the delay-difference model, but the model fit may be sensitive to these priors. To test this sensitivity, we fit the same model using different formulations for the priors on variance terms. Specifically, we tested fits using vague Gamma priors on the variances, i.e.,  $\text{Gamma}(1, 0.001)$ , and Uniform priors on the standard deviations, i.e.  $U(0, 10)$  of the random variables  $\eta$ ,  $\tau$ ,  $\epsilon$  and  $\nu$ .

## **Model comparisons**

We compare the results of the default delay-difference population model to those of a simpler surplus production model and to the virtual population analysis (VPA) model that was used to provide management advice for the Georges Bank scallop stock in past years (Robert et al. 2000).

### *Surplus production model*

We used a state-space implementation of the Schaefer surplus production model (Meyer and Millar 1999b), retaining the same observation model structure used for the delay-difference model but excluding the recruit index. The surplus production model ignores population size-structure and aggregates growth, natural mortality and recruitment processes into a single parameter, the intrinsic rate of population growth  $r$ . Changes in biomass are defined by  $r$  and affected only by the size of the population in the previous year relative to its carrying capacity  $K$ .

### *ADAPT VPA model*

The original VPA model for offshore scallops was proposed by Mohn et al. (1984) and modified periodically (Robert et al. 2000). The model is a cohort analysis with a quarterly time step, tuned using the ADAPT method (Gavaris 1988) to scallop numbers in age classes 3-8 from the survey and ages 4-8 from the second quarter CPUE. The range of ages used for tuning appears to have varied over time (Robert et al. 2000). The model uses a highly domed selectivity vector with a peak at ages 4 and 5 and a rapid decline with older ages.

## **Model Results**

### ***Biomass estimates***

The biomass estimates from the delay-difference model indicate a declining trend in the early 1980's followed by a transient increase, due to moderate and larger recruit cohorts in 1984 and 1985. Biomass then declined from 1986-1988 and then entered a period of slight rebuilding and small fluctuations from 1989-1999 (Table 11, Figure 21). Biomass rapidly increased from about 12 000 t in 1999 to 31 000 t in 2000 as large cohorts of recruits entered the fishery in 2000 and 2001; this biomass peak lasted three years and was followed by a rapid decline to about 15 000 t in 2004-2005 (Table 11, Figure 21). Increases occurred again in 2006 and 2007, due to moderate and large recruit cohorts in 2005 and 2006, and was at 26 000 t in 2007, the fourth highest biomass since 1981 (Table 11, Figure 21). The 95% credible limits on the biomass estimates suggest that biomass is estimated with reasonable precision. Larger median biomass estimates are more uncertain, as is expected for a log-normal process.

### ***Model diagnostics***

Plots of priors and posteriors of the proportionality coefficients indicated considerable information in the data for these parameters (Figure 22). Catchability appears to have been lower at a median of 0.23 in 1981-1985 compared to values of 0.40 and 0.36 for 1986-1995 and 1996-2007, respectively (Table 12). The posterior median and variance of  $K$  was substan-



tially smaller than that specified by the prior (Figure 22, Table 12). The data were mildly informative about the process stochasticity and observation errors (Figure 22); the posterior medians of the precisions,  $\sigma_{\eta}^{-2}$ ,  $\sigma_{\tau}^{-2}$  and  $\sigma_{\epsilon}^{-2}$ , were somewhat greater than specified by the priors, suggesting that the CV's were smaller than the 0.5 specified by the priors. The posterior median of  $\sigma_{\nu}^{-2}$  was also somewhat larger than that implied by the prior, again, suggesting that the CV was smaller than the 0.625 specified by the prior.

Residuals for the process noise, the fully recruited biomass and the CPUE were more variable than those for recruit biomass (Figure 23). Large residuals in the fits to the fully recruited biomass and CPUE indices appear to be primarily a result of transient conflicts between these two indices. Three large positive residuals for fully recruited biomass in 1985-86 and 1992 correspond with rapid and transient increases in the survey biomass index that were largely not supported by the CPUE index (compare Figure 23 with Figure 2 and Figure 18 B). A large negative residual in 1994 corresponds to the lowest biomass observed in the survey index after the early 1980s, which conflicts with a corresponding low in 1995 in the CPUE (compare Figure 23 with Figure 2 and Figure 18 B). In general, the model tends to fit better to the CPUE index prior to 2000 and better to the fully recruited survey index from 2000 onward.

A retrospective analysis (data systematically removed from end of time series) suggests a tendency to over-estimate biomass and under-estimate fishing mortality (F) during the period of peak biomass and the subsequent decline (2000-2003, Figure 24). Apart from this tendency to over-estimate biomass during the peak years, the biomass and F estimates were very similar to the default model fit as might be expected with a forward-projecting model. A prospective analysis (data systematically removed from start of time series) suggests mild sensitivity to initial conditions in the time series, but there was no apparent bias toward over- or under-estimation of biomass or F (Figure 25). Despite a sensitivity to the starting point of the time series, there were no clear distortions of the biomass trajectory compared to that estimated from the complete time series.

In addition to the retrospective and prospective analyses, we assessed the model's predictive ability by comparing the one year ahead biomass predictions to the biomass estimates for those same years (Figure 26). The one-year ahead predictions tend to be lower than the estimates as the stock increases and higher than the estimates as the stock declines. The predictions in 2001 and 2003 are larger than the corresponding estimates, but predictions and estimates match closely when the stock is stable. Consistent with the retrospective analysis (Figure 24), there was a tendency to both over-predict and over-estimate biomass during the peak years of 2000-2003 when using data only up to each year versus the complete time series.

## **Sensitivity analyses**

### *Growth*

The delay-difference model was sensitive to the range of growth parameters considered, with relative differences in biomass estimates ranging from approximately -11% to 12% (Table 13). Of the available growth parameters, the default values of Brown et al. (1972) appear to be conservative, with only those of Serchuk et al. (1982) yielding lower average biomass estimates.



### *Priors on variances*

Despite changing from informative priors on precision terms to largely uninformative priors on variance or standard deviations, the model fits did not differ substantially from the default implementation (Figure 27, Figure 28). The only noticeable difference was that the model with vague Gamma priors fit nearly perfectly to the recruit biomass (Figure 27b, Figure 28b).

## **Model comparisons**

### *Surplus production model*

The surplus production model estimated consistently lower biomass and higher  $F$  compared to the delay-difference model (Figure 29). Although the differences were minor in several years, the surplus production model more strongly under-estimated the 3 boom years (2000–2002). In addition, the uncertainty in biomass estimates was greater for the surplus production model (Table 14).

### *ADAPT VPA model*

Published biomass and fishing mortality estimates are available up to and including the 2005 fishing season (DFO 2006). These were compared with estimates from the delay-difference model.

Biomass estimates from the two models are similar prior to 1987, but, relative to the delay-difference estimates, the VPA over-estimates biomass from 1989 to 2001 and under-estimates biomass from 2001 to 2004 (Figure 30 a). The peak in VPA-derived biomass estimates occurred in 1999 and is inconsistent with the peak in delay-difference biomass estimates, the survey biomass index (Figure 18) and the commercial CPUE index (Figure 2 a). Despite the large discrepancies in biomass estimates from 1996 to 2004, which are associated with the large recruitment events of 1999 and 2000, the two models suggest very similar patterns in biomass trends prior to 1996. Discrepancies in  $F$  estimates (Figure 30 b) are largely due to differences in the biomass estimates, but the estimates may also differ in the calculation used. Here  $F$  is calculated as  $-\log(1 - \frac{C_{t-1}}{C_{t-1} + B_t})$ , which takes into account the productivity of the stock. Regardless, the general pattern in  $F$  is similar for the two model, with the exception of the period 1995 to 1999.

## **DISCUSSION**

### ***Population model fit***

The delay-difference model presented provides a reasonable fit to the survey and CPUE indices. Biomass estimates seem reasonable given current understanding of the resource and given previous estimates from the ADAPT VPA model. We have some concern with the lack of fit for a few years of the fully-recruited index and with some apparent conflicts between the survey fully recruited index and the CPUE index, especially in the last four years (Figure 23). From 2004 to 2007, the survey index suggests a steady increase in fully-recruited biomass (Figure 18), whereas the CPUE index suggests a small decline followed by a rapid and large increase from 2006 to 2007 (Figure 2 b). This conflict has some bearing

on the current predictive ability of the model, as the biomass trend mimics the CPUE trend in the last four years, although the 2007 estimate has a reasonably large CPUE residual (Figure 23). The large increase in CPUE from 2006 to 2007 was partly due to industry's choice to open a voluntary seed closure in 2007, but we removed fishing records from within the seedbox area from our CPUE estimate. It is possible that some of the remaining records were actually from within the seedbox, as logbook information was recorded once per day. How proportional the CPUE index is to true biomass, and how that proportionality may change in future years if the scallop industry chooses to continue using voluntary seed closures as a means for maximizing yield, is an unresolved issue.

The estimation and prediction diagnostics suggest that the current formulation of the delay-difference model is reasonably robust to removal of data both at the start and end of the current time series, showing no strong estimation biases. The model did over-estimate biomass during the peak years 2000-2002, but it is not surprising that the model would have difficulty with these unusual years. One concern during this peak year period is the relatively large under- and over-prediction as biomass increases and declines, respectively. This pattern is typical of stock assessment models (NRC 1998), but the magnitudes found here suggest that the uncertainty of harvest advice during periods of strong increasing or decreasing trends will be relatively large. It is possible that a resolution of conflict between the CPUE and survey indices will alleviate some, but not all, of this issue.

### ***Comparison to ADAPT VPA model***

The ADAPT VPA model formerly used to assess the Georges Bank scallop population is an age-structured model that suffers from strong retrospective effects and a lack of recent aging information (Lavoie 2000). The discrepancies in biomass estimates between the delay-difference and VPA models are consistent with biases introduced by the cohort slicing approach used to construct the catch-at-age matrix for the VPA (Robert et al. 2000). Cohort slicing tends to under-estimate strong cohorts and over-estimate weak cohorts, resulting in a model fit that smoothes away the large and rapid changes in stock biomass of recent years that are suggested by the survey and commercial catch rate indices. This smoothing effect resulted in conservative biomass estimates during the late 1990s and early 2000s but more reasonable estimates from 2003 to 2006 (DFO 2007). In 2007, two versions of ADAPT VPA biomass estimates and exploitation rates were rejected because they provided a poor fit to the data in recent years and because biomass projections were unrealistic given past experience with this stock (DFO 2008).

In addition, the VPA model has a strong retrospective effect (Robert et al. 2000) that suggests a potentially spurious increasing trend in biomass estimates in the 1990s. The biomass trend from the 1999 Georges Bank scallop assessment (Robert et al. 2000) indicates no long-term biomass increase (Figure 31 a). The 1999 biomass estimate was approximately 11 000 t, whereas the 1999 estimate from the 2005 stock assessment was approximately 30 000 t (Figure 31 b). The delay-difference model fit suggests that little if any long-term increase in biomass occurred prior to the large recruitment events of 1999 and 2000, which is consistent with the survey biomass index.

## Decision rules and management

There are no formally defined objectives and references points for this fishery. In the past, advice in the form of catch and exploitation scenarios have been provided relative to  $F_{0.1}$  and  $F_{max}$  fishing mortality levels obtained from standard yield-per-recruit analyses (Robert et al. 2000), but this practice was not adopted in all years that formal advice was provided. The use of standard yield-per-recruit analyses on sedentary species has been criticized because the dynamic pool assumption does not hold and fishing mortality risk can vary tremendously among individuals distributed heterogeneously in space (Caddy 1978; Hart 2001). Smith and Rago (2004) showed that large amplitude fluctuations in scallop biomass can be explained by spatial variation in habitat quality, aggregation of fishing effort and larval dispersal, and they argued that such spatially-structured influences should be considered in developing biological references points for sedentary species. Yet, despite rapid advancements in technology like acoustic multi-beam mapping, video surveys and vessel monitoring systems that allow researchers to gather ever more sophisticated and spatially referenced data, quantitative tools for making optimal use of these data are often lacking.

Here we employ a method for defining a target or removal reference point that is based on estimated exploitation rates ( $C_t/B_{t-1} + C_t$ ) and changes in biomass  $B_t - B_{t-1}$ . We plot exploitation rates against their associated changes in biomass and, ignoring the 1999-2000 episodic recruitment event, fit linear regressions to estimate the x-intercepts, i.e., the point at which the change in biomass is zero. Although the regression fit to the full time series implied a reference exploitation level of 0.25, the slope was not significant and several biomass declines occurred below an exploitation rate of 0.25 (Figure 32 a). We subsequently divided the data, splitting on years with average August meat weights greater than 18.5g (Figure 19), and fit regressions to these two subsets (Figure 32 b-c). Both regressions yielded significant slope estimates and imply quite different reference exploitation levels of 0.32 for 1981 to 1996 (excluding 1994) with meat weights less than 18.5g and 0.17 for 1997 to 2007 (including 1994) with meat weights greater than 18.5g.

Another way to think about a target reference exploitation level is to consider the balance between mortality, growth and recruitment. The delay-difference model provides a convenient method for estimating growth potential provided that average weights of fully-recruited scallops are known,  $\rho + \alpha/\bar{\omega}_{t-1}$ . By re-arranging the delay-difference process model, we can express exploitation as a function of this growth potential, discounted for natural mortality (Smith et al. 2008):

$$\begin{aligned} B_t &= \exp(-m) \left( \rho + \frac{\alpha}{\bar{\omega}_{t-1}} \right) (B_{t-1} - C_{t-1}) \\ B_t &= \exp(-m) \left( \rho + \frac{\alpha}{\bar{\omega}_{t-1}} \right) [(1 - \mu_t) B_{t-1}] \\ B_t &= (1 - \mu_t) \exp(-m) \left( \rho + \frac{\alpha}{\bar{\omega}_{t-1}} \right) B_{t-1} \end{aligned} \quad (10)$$

Setting  $B_{t+1} = B_t$  gives:

$$\begin{aligned}
 (1 - \mu'_t) \exp(-m) \left( \rho + \frac{\alpha}{\bar{\omega}_{t-1}} \right) &= 1 \\
 (1 - \mu'_t) &= \frac{1}{\exp(-m) \left( \rho + \frac{\alpha}{\bar{\omega}_{t-1}} \right)} \\
 \mu'_t &= \frac{\exp(-m) \left( \rho + \frac{\alpha}{\bar{\omega}_{t-1}} \right) - 1}{\exp(-m) \left( \rho + \frac{\alpha}{\bar{\omega}_{t-1}} \right)}
 \end{aligned} \tag{11}$$

We refer to the solution in Equation 11,  $\mu'_{t-1}$  as the replacement exploitation level, which allows for variable growth potential, discounted by a constant natural mortality, through changes in stock size structure that are indexed by  $\bar{\omega}_{t-1}$ . There isn't an immediately obvious way to include variable recruitment in this formulation, so for now we adopt a precautionary approach that ignores recruitment and stochastic perturbations. Exploitation rates above the replacement level result in biomass decline, and exploitation rates below it result in biomass increase through growth. Of course, recruitment will occur at some level, so biomass may not decline in years when exploitation exceeds the replacement level if recruitment is large enough to compensate for the fishery removals. Recruitment can also compensate for elevated exploitation by increasing the growth potential of the stock through a reduction in the average meat weight of fully-recruited scallops. These ideas are illustrated in Figure 33.

Two features of Figure 33 are immediately obvious. First increases in scallop biomass occurred even when exploitation exceeded the replacement level, largely due to the "rescuing" effect of recruitment and, conversely, no declines occurred when exploitation was below the replacement level. Second, as was illustrated by the regressions in Figure 32, a single fixed reference level is not applicable given the biomass dynamics of this stock.

If we assume that, in the current phase of the fishery, a reference exploitation level of 0.17 is reasonable, we can construct catch scenarios evaluated against this reference point. To account for uncertainties inherent in the stock assessment, we estimate the probability that exploitation will exceed the reference level of 0.17 for a given catch (Table 15). Smith and Lundy (2002b) discuss the appropriate level of uncertainty that the fishing industry and management should consider, rightly pointing out that the fishing industry may tolerate higher levels of uncertainty than is the norm in scientific fields. In fact, it is likely that the risk tolerated by industry will be variable, contingent on, for example, scallop and fuel prices, the currency exchange rate between Canada and the US, and scallop biomass levels on the other offshore banks. For these reasons, we provide a range of catches that encompass probabilities of exploitation exceeding the reference level from 0.15 to 0.7. As an example, if we are comfortable with a level of uncertainty of 0.35, then we would recommend catches of 4 500 t or less for the 2008 season, which would imply an exploitation rate of 0.15 and result in a slight decline in biomass. In fact, the fishing industry and management chose to set a final TAC in 2008 of 5 500 t, implying an exploitation rate of 0.18, a decline in biomass of 4.3% and a 0.55 probability of exceeding the reference exploitation level. Bearing in mind that the delay-difference model tends to under-predict biomass during an increasing phase as is now occurring (Figure 26), this choice does not seem unreasonable, although the recruitment in

2008 is expected to be low.

## Recommendations from the Framework Meeting

The model presented in this research document was presented at the Georges Bank scallop Framework Meeting held at the Bedford Institute of Oceanography (BIO) in February 2009. A number of recommendations for improving the model, its implementation and the provision of harvest advice were made at the meeting (DFO 2009). Here we describe how the model, its implementation and provision of harvest advice have changed as a result of these recommendations.

### Model

#### Catchability parameters

The survey catchability estimates ( $\hat{q}_1, \hat{q}_2, \hat{q}_3$ ) were high relative to those estimated from the National Marine Fishery Service (NMFS) scallop survey dredge studies (D. Hart, *pers. comm.*). The uniform prior on 0,1 may have biased the posterior estimate high, whereas a Beta prior with range between 0.2 and 0.5 would more adequately capture the range of catchabilities estimated in NMFS studies. We, consequently, used informative Beta priors, Beta(20, 40) on all three survey catchability parameters. The informative Beta priors had the effect of increasing the  $q$ 's over those estimated with Uniform priors. This, in turn, lowered the absolute biomass estimates, on average, by 18% from those estimated by the original model.

#### Index uncertainty

There was some concern that the model was fitting rather more closely to the commercial catch rate index than to the survey indices. To alleviate this we accounted for uncertainty in the survey and commercial indices in the model by altering the observation error structures for the fully recruited  $I_{f(t)}$  and recruit  $I_{r(t)}$  survey indices and for the commercial catch rate index  $U_t$ . We used the recruit and fully recruited annual survey CV's and the annual jackknifed standard deviations from the commercial catch rate index as a time-varying error component. We also estimated a fixed error component for each index to account for any additional error. This approach is more satisfactory than fitting to point estimates because it explicitly acknowledges that the annual indices are summaries of multiple observations that are subject to error and spatial variability. The revised log-normal random variables  $\tau_t$ ,  $\epsilon_t$  and  $\nu_t$  now have the following form:

$$\tau_t \sim \text{LN}(0, \sigma_\tau^2 + \text{CV}_{I_f(t)})$$

$$\epsilon_t \sim \text{LN}(0, \sigma_\epsilon^2 + \text{CV}_{I_r(t)})$$

$$\nu_t \sim \text{LN}(0, \sigma_\nu^2 + \text{CV}_{U(t)})$$

This approach had the desired effect of slightly down-weighting the fit to the commercial



catch rate index and improving the fit to the fully recruited biomass. A comparison of DIC's (Deviance Information Criterion, Spiegelhalter et al. 2002) between this revised model (DIC = 1023.7) and the original model (DIC = 1054.8) favours accounting for index uncertainty within the model.

## **Model Implementation**

### **Survey design**

Following the recommendation of the Framework meeting, a new survey design, based on a stratification by historical survey abundance, was adopted for Georges Bank (Hubiey et al. 2009). This design was imposed on the existing survey data and the model was fit to the new survey indices.

## **Advice**

### **Production analysis**

Notwithstanding acknowledged difficulties in using traditional finfish approaches for establishing biological reference points for nearly sessile species (Smith and Rago 2004), we examined production, yield and stock-recruit curves to determine whether these tools could be useful in establishing biological reference points for the Georges Bank 'a' scallop stock.

The production plot provides evidence of retarded production at biomass levels below approximately 7 500 t and a possible maximum production at approximately 22 000 t (Figure 34a). The yield plot suggests little relationship between catches and fully recruited biomass (Figure 34b). Similarly, the stock-recruit plot implies little evidence of a relationship; the smallest and largest recruit cohorts came from the same biomass range of 7 500 to 10 000 t (Figure 34c). Finally, the phase plot of  $F$  and fully recruited biomass displays two distinct regimes to the fishery (Figure 34d); a high exploitation/low biomass regime prior to 1999 (excluding 1995-96) with an average  $F$  of 0.4 and average biomass of 9,400 t and a low exploitation/high biomass regime from 1999 onward with an average  $F$  of 0.21 and average biomass of 19 000 t.

These results imply that the use of traditional approaches for developing biological reference points for scallops are not fruitful. The slight evidence for reduced production when biomass declines below 7 500 t could be used to specify a precautionary lower biomass threshold.

### **Harvest decision table**

The proposed decision table (Table 15) was based on providing advice against the exploitation rate associated with no change in biomass. This approach is cumbersome given that the replacement analysis shows that the exploitation rate associated with no change in biomass is a function of stock size structure (Figure 33) and, therefore, will change from year to year. Consequently, a new decision table was adopted where harvest levels and associated exploitation rates were evaluated against the probability of a biomass decline (Table 16). Additionally, harvest levels evaluated were those within the historical range experienced on

Georges Bank (1981-2007), in 500 t increments. The harvest level corresponding with no projected change in biomass was also provided.

## ACKNOWLEDGEMENTS

We thank Dvora Hart for providing growth rate parameters obtained from the Canadian portion of the US scallop survey and for generously offering to fit her CASA model to the Canadian scallop survey data. We also thank Stephen Smith for many helpful discussions and for reformulating the delay-difference process equation to calculate the replacement level. Finally, we thank Captain Ross Hartman of the Cape Keltic/E.E. Pierce/Tenacity, his crew and Jim Mosher of Clearwater Fine Seafoods for making the annual surveys possible.

## References

- Akima, H. 1978. A method of bivariate interpolation and smooth surface fitting for irregularly distributed data points. *ACM Transactions on Mathematical Software* **4**: 148-164.
- Black, G. A. P., Mohn, R. K., and Tremblay, M. J. 1993. Atlas of the biology and distribution of the sea scallop *Placopecten magellanicus* and Iceland scallop *Chlamys islandica* in the Northwest Atlantic. Canadian Technical Report Fisheries and Aquaculture Science **No. 1915**: 34 p.
- Bourgeois, M., Brethes, J. C., and Nadeau, M. 2006. Substrate effects on survival, growth and dispersal of juvenile sea scallop, *Placopecten magellanicus* (Gmelin 1791). *Journal of Shellfish Research* **25**: 43-49.
- Bourne, N. 1964. Scallops and the offshore fishery of the Maritimes. Fisheries Research Board of Canada **Bulletin No. 145**.
- Brown, B. E., Parrack, M., and Flescher, D. D. 1972. Review of the current status of the scallop fishery in International Commission for the Northwest Atlantic Fisheries (ICNAF) Division 5Z. ICNAF Research Document **72/113, Serial No. 2829**: 13 p.
- Caddy, J. F. 1978. Spatial models for an exploited shellfish population, and its application to the Georges Bank scallop fishery. *Journal of the Fisheries Research Board of Canada* **32**: 1305-1328.
- Culliney, J. L. 1974. Larval development of the giant scallop *Placopecten magellanicus* (Gmelin). *Biological Bulletin* **147**: 321-332.
- Deriso, R. B. 1980. Harvesting strategies and parameter estimation for an age-structured model. *Canadian Journal of Fisheries and Aquatic Sciences* **37**: 268-282.
- DFO, 2003. Georges Bank scallop. DFO Science Stock Status Report **2003/038**: 11 p.
- DFO, 2006. Assessment of Georges Bank scallops (*Placopecten magellanicus*). DFO Canadian Science Advisory Secretariat Science Advisory Report **2006/032**: 11 p.



- DFO, 2007. Assessment of Georges Bank scallops (*Placopecten magellanicus*). DFO Canadian Science Advisory Secretariat Science Advisory Report **2007/026**: 8 p.
- DFO, 2008. Assessment of Georges Bank scallops (*Placopecten magellanicus*). DFO Canadian Science Advisory Secretariat Science Advisory Report **2008/045**: 12 p.
- DFO, 2009. Proceedings of a Maritimes Science Advisory Process to develop a new assessment framework for Georges Bank scallop; 18-20 February 2009. DFO Canadian Science Advisory Secretariat Proceedings Series **2009/029**: iv + 30 p.
- Gavaris, S. 1988. An adaptive framework for the estimation of population size. CAFSAC Research Document **88/29**: 12 p.
- Hart, D. R. 2001. Individual-based yield-per-recruit analysis, with an application to the Atlantic sea scallop, *Placopecten magellanicus*. Canadian Journal of Fisheries and Aquaculture Science **58**: 2351–2358.
- Hilborn, R., and Walters, C. J. 1992. Quantitative fisheries stock assessment: Choice, dynamics and uncertainty. Chapman and Hall, New York.
- Hubley, B., Smith, S. J., Jonsen, I. D., and Sameoto, J. 2009. Georges Bank 'a' scallop (*placopecten magellanicus*) annual stock assessment: Survey design. DFO Canadian Science Advisory Secretariat Research Document **2009/33**: vi + 43 p.
- Jonsen, I. D., Myers, R. A., and Mills Flemming, J. 2003. Meta-analysis of animal movement using state-space models. Ecology **84**: 3055–3063.
- Kostylev, V. E., Courtney, R. C., Robert, G., and Todd, B. J. 2003. Stock evaluation of giant scallop (*Placopectin magellanicus*) using high-resolution acoustics for seabed mapping. Fisheries Research **60**: 479–492.
- Kostylev, V. E., Todd, B. J., Fader, G. B. J., Courtney, R. C., Cameron, G. D. M., and Pickrill, R. A. 2001. Benthic habitat mapping on the Scotian Shelf based on multibeam bathymetry, surficial geology and sea floor photographs. Marine Ecology Progress Series **219**: 121–137.
- Lavoie, R. (Chairperson). 2000. Proceedings of the Maritimes Regional Advisory Process of the Georges Bank scallop stock. CSAS Proceedings Series **2000/13**: 12 p.
- Lunn, D. J., Thomas, A., Best, N., and Spiegelhalter, D. 2000. WinBUGS - A Bayesian modelling framework: concepts, structure, and extensibility. Statistics and Computing **10**: 325–337.
- MacDonald, B. A. 1984. The portioning of energy between growth and reproduction in the giant scallop, *Placopecten magellanicus* (Gmelin). PhD Thesis, Memorial University, St. John's, Nfld.
- Meyer, R., and Millar, R. B. 1999a. Bayesian stock assessment using a state-space implementation of the delay difference model. Canadian Journal of Fisheries and Aquatic Sciences **56**: 37–52.

- Meyer, R., and Millar, R. B. 1999b. BUGS in Bayesian stock assessments. *Canadian Journal of Fisheries and Aquatic Sciences* **56**: 1078–1086.
- Mohn, R. K., Robert, G., and Roddick, D. L. 1984. Georges Bank scallop stock assessment - 1983. CAFSAC Research Document **84/12**: 29 p.
- Naidu, K. S., and Robert, G. 2006. Fisheries sea scallop, *Placopecten magellanicus*; 869–905 pp. *In*: *Scallops: Biology, Ecology and Aquaculture* (2nd Edition). Edited by S. E. Shumway and G. J. Parsons. Elsevier, New York.
- NRC 1998. Improving methods for fish stock assessment. National Academy Press, Washington.
- Pella, J. J., and Tomlinson, P. K. 1969. A generalized stock production model. *Inter-American Tropical Tuna Commission Bulletin* **16**: 283–400.
- Posgay, J. A. 1962. Maximum yield per recruit of sea scallops. ICNAF Annual Meeting Series 1016, Document **73(1016)**: 20 p.
- Posgay, J. A. 1976. Population assessment of the Georges Bank sea scallop stocks. ICES C.M. **K.34**: 6 p.
- Posgay, J. A. 1979. Population assessment of the Georges Bank sea scallop stocks. *Rapp. P.-v. Reun. Cons. Int. Explor. Mer.* **175**: 109–113.
- Quinn, T. J., and Deriso, R. B. 1999. *Quantitative Fish Dynamics*. Oxford University Press, New York.
- Robert, G., and Jamieson, G. S. 1986. Commercial fishery data isopleths and their use in offshore sea scallop (*Placopecten magellanicus*) stock evaluations. *Special Publication of the Canadian Fisheries and Aquatic Sciences* **92**: 76–82.
- Robert, G., Black, G. A. P., and Butler, M. A. E. 1994. Georges Bank scallop stock assessment - 1993. DFO Atlantic Fisheries Research Document **94/97**: 42 p.
- Robert, G., Black, G. A. P., and Smith, S. J. 2000. Georges Bank scallop stock assessment - 1999. CSAS Research Document **2000/016**: 84 p.
- Roddick, D. L., and Mohn, R. K. 1985. Use of age-length information in scallop assessments. CAFSAC Research Document **85/37**: 16 p.
- Schaefer, M. B. 1954. Some aspects of the dynamics of populations important to the management of commercial marine fisheries. *Inter-American Tropical Tuna Commission Bulletin* **1**: 27–56.
- Schick, D. F., Shumway, S. E., and Hunter, M. 1988. A comparison of growth rate between shallow water and deep water populations of scallops, *Placopecten magellanicus* (Gmelin, 1791) in the Gulf of Maine. *American Malacological Bulletin* **6**: 1–8.
- Schnute, J. T. 1985. A general theory for analysis of catch and effort data. *Canadian Journal of Fisheries and Aquatic Sciences* **42**: 414–429.

- Serchuk, F. M., Wood, P. W. J., and Rak, R. S. 1982. Review and assessment of the Georges Bank, mid-Atlantic and Gulf of Maine Atlantic sea scallop (*Placopecten magellanicus*) resources. Nat. Mar. Fish. Serv., Woods Hole Oceanographic Inst. Ref. Doc. **82-06**: 132 p.
- Shumway, S. E., and Parsons, G. J. 2006. Scallops: Biology, Ecology and Aquaculture. Elsevier, Boston.
- Smith, S. 1980. Comparison of 2 methods of estimating the variance of the estimate of catch per unit effort. Canadian Journal of Fisheries and Aquatic Sciences **37**(12): 2346–2351.
- Smith, S. J., and Lundy, M. 2002a. Scallop Production Area 3 and Scallop Fishing Area 29: Stock status and forecast. DFO Canadian Science Advisory Secretariat Research Document **2002/017**: 74 p.
- Smith, S. J., and Lundy, M. 2002b. Scallop production in Area 4 in the Bay of Fundy: Stock status and forecast. DFO Canadian Science Advisory Secretariat Research Document **2002/018**: 90 p.
- Smith, S. J., and Rago, P. 2004. Biological reference points for sea scallops (*Placopecten magellanicus*): The benefits and costs of being nearly sessile. Canadian Journal of Fisheries and Aquatic Sciences **61**: 1338–1354.
- Smith, S. J., and Robert, G. 1998. Getting more out of your survey design: an application to Georges Bank scallops (*Placopecten magellanicus*); 3-13 pp. In: Proceedings for the North Pacific Symposium on Invertebrate Stock Assessment and Management. Edited by G. S. Jamieson and A. Campbell. Special Publication of the Canadian Fisheries and Aquatic Sciences, 125.
- Smith, S. J., Lundy, M., Sameoto, J., and Hubley, B. 2008. Scallop Production Areas in the Bay of Fundy: Stock Status for 2008 and Forecast for 2009. DFO Canadian Science Advisory Secretariat Research Document **2008/22**: vi + 108 p.
- Spiegelhalter, D. J., Best, N. G., Carlin, B. R., and van der Linde, A. 2002. Bayesian measures of model complexity and fit. Journal of the Royal Statistical Society Series B **64**: 583–616.
- Stevens, G., Robert, G., Burke, L., Poullioux, E., Roussel, D., and Wilson, J. R. 2008. The evolution of management in Canada's offshore scallop fishery. Case Studies in Fisheries Self-Governance: 111–123.
- Stevenson, J. A., and Dickie, L. M. 1954. Annual growth rings and rate of growth of the giant scallop, *Placopecten magellanicus* (Gmelin) in the Digby area of the Bay of Fundy. Journal of the Fisheries Research Board of Canada **11**: 660–671.
- Thouzeau, G., Robert, G., and Smith, S. J. 1991. Spatial variability in distribution and growth of juvenile and adult sea scallops *Placopecten magellanicus* (Gmelin) on eastern Georges Bank (Northwest Atlantic). Marine Ecology Progress Series **74**: 205–218.
- Wong, M. C., Wright, L. D., and Barbeau, M. A. 2006. Sediment selection by juvenile sea scallops (*Placopecten magellanicus* (Gmelin)), sea stars (*Asteris vulgaris verrill*) and rock crabs (*Cancer irroratus* Say). Journal of Shellfish Research **25**: 813–821.

**Table 1.** History of the fishery on Georges Bank 'a'. Class 1 data refer to observations from logbooks where catch, effort and position were all reported. Total catch was calculated from logbook data using all observations.  $p_a$  is the proportion of reported fishing locations on Georges Bank 'a' and is used to estimate Georges Bank 'a' catch for the period 1981-1997 from the total reported on Georges Bank. N is the number of logbook observations. From 1998 onward, catches on Georges Bank are recorded separately for zones 'a' and 'b'. TAC's are for the entire Canadian portion of Georges Bank from 1986-1997 and for Georges Bank 'a' only from 1998 to present.

Year	Class 1 Data			$p_a$	N	TAC (meats, t)
	Catch (meats, t)	Effort ( $\times 10^3$ hm)	CPUE (kg/hm)			
1981	9195.45	690.42	9.19	0.95	8135	
1982	4149.54	492.43	6.52	0.79	6131	
1983	2766.28	494.46	4.41	0.85	5554	
1984	2702.56	466.85	3.22	0.93	5065	
1985	3741.11	787.23	4.27	0.98	7169	
1986	4876.54	370.95	11.37	1.00	3588	4300
1987	6758.31	559.19	10.15	0.99	5228	6850
1988	4227.42	620.87	5.78	0.97	5521	5400
1989	4632.01	561.42	6.92	0.99	4983	4700
1990	4948.75	531.29	8.19	0.95	4686	5200
1991	5737.49	539.76	9.43	0.99	4235	5800
1992	5902.89	597.13	9.06	0.96	4641	6200
1993	5988.35	512.55	10.62	0.97	4031	6200
1994	4363.53	514.02	8.28	0.87	4074	5000
1995	1894.13	338.10	5.51	0.95	2447	2000
1996	2990.58	288.72	10.21	1.00	2225	3000
1997	4203.05	324.83	12.92	0.99	2667	4250
1998	3191.00	366.96	7.98	0.80	3328	3200*
1999	2503.00	201.11	10.45	0.68	2669	2500*
2000	6212.00	172.60	36.53	0.91	2872	6200*
2001	6480.00	286.83	21.15	0.94	3396	6500*
2002	6469.00	171.02	36.59	0.97	3148	6500*
2003	5985.00	398.83	14.75	0.97	3190	6000*
2004	3518.00	329.34	10.14	0.95	2454	3500*
2005	2484.00	259.47	9.24	0.92	1876	2500*
2006	3932.00	312.03	11.97	0.96	2332	4000*
2007	4000.00	140.78	29.08	0.91	1721	4000*

\*TAC's apply to Georges Bank 'a' only

**Table 2.** Average meat weight (g) by month from port sampling of Georges Bank 'a' landings. Annual estimates are the average of monthly estimates weighted by monthly catch reported in fishing logs (class 1 data only). Maximum average meat weights in each year are highlighted in bold.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1981	—	8.96	11.00	10.19	11.58	<b>11.98</b>	11.44	10.42	9.79	6.97	8.23	8.04	10.52
1982	—	—	13.74	13.56	14.59	15.32	17.17	17.24	<b>21.36</b>	12.19	—	—	13.10
1983	—	—	8.91	11.99	12.57	16.90	19.04	<b>21.40</b>	14.72	—	16.90	14.84	12.62
1984	—	17.67	<b>18.53</b>	14.79	13.68	14.19	13.91	14.38	10.28	14.12	12.56	12.13	13.98
1985	—	—	14.30	<b>14.76</b>	14.08	13.66	13.49	14.06	14.27	12.60	12.85	12.69	13.68
1986	15.49	16.68	15.75	15.13	15.49	<b>17.08</b>	16.66	16.57	15.87	16.55	16.60	17.30	16.00
1987	16.91	17.31	16.11	15.83	16.86	<b>19.06</b>	15.70	15.87	15.69	15.39	15.06	15.79	16.44
1988	—	<b>17.35</b>	14.81	16.23	17.21	16.68	16.41	15.53	—	15.38	14.57	15.88	15.73
1989	15.45	15.54	15.39	14.89	15.35	<b>16.17</b>	—	—	—	14.30	14.89	12.96	13.10
1990	14.00	13.15	13.70	16.52	<b>17.47</b>	16.22	16.65	16.69	15.43	16.94	16.54	16.79	15.56
1991	16.52	16.05	16.71	17.38	16.84	17.15	<b>17.47</b>	16.77	16.40	17.49	16.3	16.11	16.94
1992	16.35	16.43	16.35	17.02	17.91	<b>18.54</b>	16.95	16.35	16.71	15.93	15.42	15.69	16.84
1993	16.18	15.92	16.37	16.28	16.59	17.02	17.57	<b>17.87</b>	16.59	16.78	16.42	17.08	16.64
1994	18.66	17.67	17.57	19.58	17.87	17.85	<b>20.59</b>	18.60	18.58	18.92	20.48	18.22	18.53
1995	18.80	19.66	19.03	20.44	22.05	23.32	<b>21.81</b>	21.39	18.03	18.17	17.45	18.02	20.81
1996	14.90	16.56	16.30	16.11	<b>17.68</b>	17.59	16.90	16.49	16.79	16.82	16.47	16.11	16.81
1997	16.21	16.74	17.08	18.14	19.69	21.55	21.66	<b>22.05</b>	19.07	18.39	18.97	18.27	19.12
1998	17.62	18.51	18.53	20.24	<b>22.47</b>	21.78	22.03	19.81	19.11	20.60	20.18	19.17	20.27
1999	22.56	21.54	24.24	<b>22.64</b>	21.41	19.63	20.80	21.72	17.21	18.01	18.44	21.41	20.87
2000	22.32	22.60	24.37	26.10	<b>27.06</b>	26.77	24.80	27.11	23.52	23.39	21.69	19.08	24.87
2001	26.31	27.44	28.50	<b>28.90</b>	27.18	27.57	26.82	26.62	21.60	19.05	19.59	20.21	25.39
2002	20.03	20.08	19.73	21.53	26.75	30.50	<b>31.32</b>	30.40	26.35	22.20	22.66	23.30	25.67
2003	22.69	22.63	22.01	24.81	28.69	28.93	<b>32.10</b>	27.44	23.91	21.20	23.72	22.81	25.39
2004	21.94	22.42	22.98	22.60	24.10	<b>25.01</b>	24.25	23.59	20.75	19.00	20.06	21.05	22.31
2005	19.08	18.54	20.28	18.87	18.60	<b>22.64</b>	21.38	20.87	18.56	18.41	20.39	20.88	19.87
2006	17.33	17.78	19.00	20.95	21.20	<b>22.13</b>	21.80	20.65	19.01	19.36	20.41	20.03	20.61
2007	21.00	22.63	21.51	23.09	22.67	24.90	<b>27.37</b>	23.73	21.46	21.32	—	—	23.68

**Table 3.** Original and reconstructed strata definitions for the commercial catch rate-stratified survey design.

Stratum	Strata definitions	
	Original <sup>1</sup> kg/crhm	Reconstructed kg/hm
1	0.01	0
2	0.20	4
3	0.50	9
4	1.00	18
5	2.00	36

<sup>1</sup>From (Robert et al. 2000)

**Table 4.** Reconstructed Georges Bank 'a' strata areas in towable units (1950.72 m<sup>2</sup>).

Year	Strata				
	1	2	3	4	5
1981	3771.46	821.07	979.34	54.41	0.00
1982	3917.37	1349.07	326.45	33.39	0.00
1983	4766.88	816.12	43.28	0.00	0.00
1984	5519.93	106.34	0.00	0.00	0.00
1985	5016.66	605.91	3.71	0.00	0.00
1986	4073.18	894.02	631.87	27.20	0.00
1987	3571.14	880.42	1153.70	21.02	0.00
1988	3437.59	2141.69	46.99	0.00	0.00
1989	3689.85	1873.36	63.06	0.00	0.00
1990	3473.45	2003.20	149.62	0.00	0.00
1991	3445.01	1506.11	672.68	2.47	0.00
1992	3138.35	1999.49	488.43	0.00	0.00
1993	3017.17	1277.35	1321.87	9.89	0.00
1994	2998.62	1769.49	858.16	0.00	0.00
1995	4437.96	1177.19	11.13	0.00	0.00
1996	4390.97	735.74	462.47	37.10	0.00
1997	4326.67	513.17	692.46	93.98	0.00
1998	3829.58	1392.35	404.35	0.00	0.00
1999	4204.25	1231.60	154.57	35.86	0.00
2000	4849.73	81.61	127.36	293.06	274.51
2001	3960.65	306.66	698.65	561.39	98.92
2002	4388.49	302.95	437.74	291.82	205.27
2003	3995.27	364.78	817.36	336.34	112.53
2004	3254.58	1252.62	1106.71	12.37	0.00
2005	4066.99	1010.26	549.03	0.00	0.00
2006	4420.64	708.54	434.03	63.06	0.00
2007	3832.05	1145.04	310.37	217.63	121.18
2008	4411.99	234.94	717.20	254.73	7.42



**Table 5.** Von Bertalanffy growth parameter estimates for sea scallop growth rates on Georges Bank. Modified from Naidu and Robert (2006). Parameters used in the default delay-difference model are in **bold**.

Parameter			Location	Source
$L_{\infty}$	$k$	$t_0$		
148.9	0.26	1.00	Georges Bank	Posgay 1962
146.5	0.30	1.32	Northeast Peak	Posgay 1962
141.8	0.28	1.00	Northern Edge	Posgay 1962
<b>145.5</b>	<b>0.38</b>	<b>1.50</b>	<b>Georges Bank</b>	<b>Brown et al. 1972</b>
146.4	0.35	1.40	Georges Bank	Posgay 1976
143.6	0.37	1.00	Georges Bank	Posgay 1979
152.5	0.34	-1.45	Georges Bank	Serchuk et al. 1982
161.4	0.18	1.20	Georges Bank*	Roddick and Mohn 1985
133.7	0.45	0.50	Georges Bank*†	Hart (pers. comm.)

\* Canadian side only

† Parameters provided by D. Hart were estimated from 287 scallop shells collected between 2001 and 2007.

**Table 6.** Average meat weight (g) at shell height (mm) for scallops from August survey of Georges Bank 'a' from 1982 to 1996.

Shell height	1982	1983	1984	1985	1986	1987	Meat weight (g)									
	1988	1989	1990	1991	1992	1993	1994	1995	1996							
50	1.15															
55	2.47		2.01													
60	2.82		2.27													
65	3.81	2.95	3.43			2.58										
70	4.29	3.86	3.83	4.58	5.47	3.82	3.92							4.89	3.71	
75	5.56	4.36	5.02	5.32	5.36	5.40	5.41	5.14	5.47			5.29	4.35	4.87	3.72	
80	7.06	5.81	6.17	6.70	6.90	6.22	6.44	6.75	7.20	5.61	6.26	6.70	6.18	4.96	5.58	
85	8.46	7.50	7.90	8.02	8.60	8.20	8.20	8.50	8.12	8.56	8.69	8.19	7.09	8.40	7.67	
90	10.35	9.54	9.41	9.70	10.12	9.65	9.66	9.86	10.04	9.27	10.27	9.35	8.28	10.04	9.24	
95	12.51	11.21	11.07	11.88	12.33	11.56	11.02	10.83	11.50	11.21	11.78	10.43	9.59	11.37	11.09	
100	14.48	12.62	12.78	13.74	14.34	13.96	12.74	12.90	12.82	13.67	13.27	12.67	11.39	12.75	12.83	
105	16.44	14.56	14.48	15.33	17.16	15.10	14.61	15.04	15.68	15.33	14.90	14.85	13.60	14.61	14.61	
110	19.53	16.82	15.69	17.02	20.43	18.29	17.77	17.56	18.22	17.21	16.51	17.11	16.04	17.42	15.73	
115	22.28	20.34	18.77	21.51	24.77	21.64	19.32	21.08	22.06	19.44	20.24	20.04	19.11	19.63	17.74	
120	26.36	23.63	22.92	25.84	29.38	26.51	22.91	23.49	25.37	21.96	22.77	23.69	21.20	23.94	21.07	
125	28.74	28.06	29.08	27.59	34.27	31.40	29.76	27.01	26.57	28.00	24.72	26.20	25.07	26.58	24.75	
130	37.64	33.73	31.84	30.20	37.93	36.60	34.46	32.65	30.24	33.10	26.49	29.39	31.00	34.48	28.56	
135	43.57	37.19	36.85	37.66	46.91	39.76	39.47	36.53	38.76	36.37	30.87	33.21	33.59	37.53	33.02	
140		44.39	41.09	49.40	53.58	50.60		45.83	41.93	42.52	34.14	43.18	35.96	44.89	40.47	
145	46.06	40.72	41.73	46.73	59.09			47.94	51.79	44.12		45.11	37.63	42.47	44.34	
150		45.57	47.52	51.69	63.34	62.90		49.12		51.55		50.35	53.20	53.42	42.30	
155		45.68	66.09	47.39	69.81	55.75		64.49				52.72		42.71	57.70	
160		51.23	65.94	62.91	64.78					65.80					56.13	
165																
170																
175																

**Table 7.** Average meat weight (g) at shell height (mm) for scallops from the August survey of Georges Bank 'a' from 1997 to 2007.

Shell height	Meat weight (g)										
	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
50											
55											
60											
65											
70							4.52	2.85	3.77		
75	3.84		5.84			5.88		5.02	4.77		11.62
80	5.84	7.77	7.70	6.81		6.90	7.40	6.33	6.21	7.99	
85	7.80	8.13	8.50	8.56	8.79	8.01	7.69	8.18	7.84	11.09	8.37
90	9.82	10.76	11.32	10.01	10.97	10.64	10.23	10.25	9.36	9.83	11.33
95	11.96	11.46	13.91	11.72	12.83	12.51	13.55	12.72	11.37	11.48	12.68
100	13.70	12.44	16.32	15.08	15.32	15.27	14.38	14.05	12.94	13.72	15.02
105	15.53	14.92	19.25	18.24	17.98	17.52	16.20	15.54	15.03	16.66	17.81
110	17.15	17.11	21.39	22.02	20.36	20.37	19.62	18.12	17.40	19.90	20.38
115	20.55	20.91	21.80	25.11	21.66	23.49	23.96	21.09	21.02	21.57	23.04
120	23.70	24.62	24.99	28.69	24.88	27.83	26.56	24.12	23.87	26.04	27.35
125	26.97	26.71	28.58	33.19	30.14	31.86	29.39	28.07	25.39	27.67	32.04
130	29.17	30.82	33.97	35.97	35.94	34.77	32.96	31.57	26.76	29.22	33.78
135	35.40	33.87	39.66	40.50	40.39	36.21	37.69	34.40	31.99	30.59	37.50
140	41.11	36.44	50.92	41.51	40.72	42.77	41.32	39.38	39.03	39.75	38.95
145	44.71	31.92	49.41	51.89	47.85	45.48	48.57	41.38	41.13	41.80	39.92
150	48.51	44.18	54.36	49.32	50.19	56.57	51.01	51.08	47.27	50.16	47.98
155	55.81		54.36	57.05	53.12		61.35	50.31	50.90	48.07	54.25
160	63.60		58.86	59.57		44.42		49.48	48.22	46.88	68.47
165	55.91			73.74					55.67	51.34	
170											
175											

**Table 8.** Fixed effects parameter estimates for shell height - meat weight relationship among years (1982-2007).

Term	Estimate	SE	df	<i>t</i> -value	<i>p</i> -value
A	-11.65	0.15	16596	-76.77	0
B	3.12	0.03	16596	96.80	0

**Table 9.** Random effects parameter estimates for shell height - meat weight relationship among years (1982-2007).

year	a	b	year	a	b
1982	-11.63	3.12	1995	-12.46	3.28
1983	-12.53	3.29	1996	-11.37	3.03
1984	-11.81	3.14	1997	-11.67	3.11
1985	-11.73	3.13	1998	-11.63	3.10
1986	-12.79	3.38	1999	-11.03	3.01
1987	-12.82	3.37	2000	-12.10	3.24
1988	-11.71	3.12	2001	-11.11	3.02
1989	-11.42	3.06	2002	-11.70	3.14
1990	-11.53	3.09	2003	-11.38	3.07
1991	-11.87	3.15	2004	-11.18	3.02
1992	-10.28	2.81	2005	-11.38	3.04
1993	-12.21	3.22	2006	-10.65	2.90
1994	-12.74	3.32	2007	-10.25	2.84

**Table 10.** Data used to fit Delay-Difference model for Georges Bank 'a'. There was no distinction between Georges Bank 'a' and 'b' prior to 1998. To obtain catches from 1981 to 1997 for the Georges Bank 'a' region, we scaled the total catch by the proportion of reported fishing locations, from class 1 logbook data, on Georges Bank 'a'.

Year	Fully recruited		Recruit	CPUE	Catch (t)
	Biomass (t)	Avg Weight (g)	Biomass (t)	(kg/hm)	
1981	1820.16	11.73	602.26	9.19	4149.54
1982	1743.27	15.33	388.80	6.52	2766.28
1983	1524.04	14.97	201.41	4.41	2702.56
1984	1021.86	11.96	929.38	3.22	3741.11
1985	3482.37	9.38	2430.84	4.27	4876.54
1986	9210.60	15.45	1977.54	11.37	6758.31
1987	4851.26	16.48	1356.97	10.15	4227.42
1988	3821.28	14.50	1898.33	5.78	4632.01
1989	4371.83	14.54	2163.90	6.92	4948.75
1990	3233.19	17.26	1317.61	8.19	5737.49
1991	3699.17	17.26	1648.50	9.43	5902.89
1992	8645.15	14.61	3173.66	9.06	5988.35
1993	5162.93	16.12	1392.96	10.62	4363.53
1994	2076.86	19.53	158.24	8.28	1894.13
1995	2724.49	17.81	1403.77	5.51	2990.58
1996	4735.88	18.00	1559.50	10.21	4203.05
1997	3270.51	22.63	698.30	12.92	3194.12
1998	2418.00	24.91	562.09	7.98	2498.75
1999	3416.86	24.41	4786.06	10.45	6180.70
2000	12243.91	25.60	6489.86	36.53	6469.61
2001	14570.25	22.75	2705.38	21.15	6456.64
2002	12536.14	26.30	1740.57	36.59	5984.63
2003	9492.82	26.36	1255.73	14.75	3523.94
2004	5486.86	27.50	1083.23	10.14	2481.88
2005	6117.09	22.93	2286.62	9.24	3931.83
2006	6775.39	22.70	3710.36	11.97	4000.52
2007	7545.41	25.20	1001.15	26.69	—

**Table 11.** Delay-difference model estimates of fully-recruited biomass and recruit biomass for Georges bank 'a'. Posterior medians are labelled 0.5, columns labelled 0.025 and 0.975 are the lower and upper limits of the 95% credible interval.

Year	Fully-recruited Biomass (t)			Recruit Biomass (t)		
	0.025	0.5	0.975	0.025	0.5	0.975
1981	5684.98	8528.50	14340.00	1244.97	2629.50	5503.02
1982	4855.00	7482.00	12700.25	856.69	1775.50	3792.12
1983	4256.98	6260.00	10500.00	477.87	1023.00	2278.07
1984	3203.97	5121.50	8623.12	2460.97	4832.00	9734.10
1985	5006.97	8347.00	14910.00	4845.93	9811.50	18960.00
1986	10050.00	15390.00	27090.25	2145.92	4656.50	9353.52
1987	7670.95	11930.00	21110.75	1569.97	3323.00	6887.20
1988	6044.93	9427.50	15690.50	2316.97	4664.00	9599.10
1989	6345.70	9941.00	16780.50	2552.97	5277.00	10630.00
1990	7150.95	10620.00	17410.50	1755.97	3713.00	7739.02
1991	7233.00	11110.00	18620.00	2222.95	4623.00	9709.02
1992	8133.35	12890.00	23330.25	3323.00	6876.00	14060.50
1993	7643.85	11900.00	21170.50	1600.97	3314.00	7057.15
1994	5406.00	8530.00	14560.00	255.89	531.00	1253.02
1995	4907.90	7823.50	13280.75	1900.92	3931.00	8427.30
1996	7299.00	11610.00	20200.00	2014.98	4345.00	9016.20
1997	7315.90	11830.00	20550.25	994.30	2122.00	4639.10
1998	5950.92	9854.50	16810.25	877.99	1868.00	4311.20
1999	6917.95	11770.00	20940.25	8102.85	15830.00	32480.50
2000	18599.50	31455.00	57580.00	6671.55	14920.00	31301.00
2001	21190.00	34300.00	60181.00	3107.73	7104.00	15430.25
2002	20899.75	34500.00	61610.00	2148.00	4644.00	10080.50
2003	13920.00	22675.00	40860.25	1568.00	3466.00	7542.02
2004	9894.65	16000.00	27760.00	1480.97	3150.50	6863.00
2005	9277.90	15060.00	26260.25	2823.95	6214.50	13140.00
2006	10859.75	17760.00	31161.00	4433.82	9810.00	20530.00
2007	15309.75	26130.00	47120.00	1379.88	3003.50	6897.65



**Table 12.** Posterior distribution summaries for key parameter estimates from the delay-difference model. The columns labelled 0.025 and 0.975 are the lower and upper limits of the 95% credible interval. The standard deviation estimate (SD) is not adjusted for autocorrelation among MCMC samples.

Parameter	Mean	SD	0.025	0.5	0.975
$K$	4022.81	982.30	2483.00	3895.00	6312.12
$q_1$	0.2364	0.0432	0.1608	0.2332	0.3278
$q_2$	0.4042	0.0648	0.2801	0.4028	0.5367
$q_3$	0.3605	0.0652	0.2428	0.3570	0.4976
$q_U$	0.0008	0.0001	0.0006	0.0008	0.0010
$\sigma_\eta$	0.3146	0.0576	0.2207	0.3080	0.4454
$\sigma_\tau$	0.3528	0.0572	0.2557	0.3480	0.4782
$\sigma_\epsilon$	0.3614	0.0856	0.2318	0.3483	0.5624
$\sigma_\nu$	0.2816	0.0468	0.2051	0.2767	0.3890

**Table 13.** Average relative difference of biomass estimates ( $\bar{\delta}_B$ ) between each published von Bertalanffy growth parameter set and the default delay-difference parameterization (in **bold**). Both the von Bertalanffy parameters for shell height growth and the corresponding linear parameters for meat weight growth are presented. The average relative difference was calculated over the 27 (1981-2007) posterior median biomass estimates from each model fit.

Height			Weight		$\bar{\delta}_B$
$L_\infty$	$k$	$t_0$	$\alpha$	$\rho$	
<b>145.5</b>	<b>0.38</b>	<b>1.5</b>	<b>9.47</b>	<b>0.82</b>	—
148.9	0.26	1.0	6.53	0.90	0.075
146.5	0.30	1.32	7.23	0.88	0.056
141.8	0.28	1.0	6.27	0.88	0.123
146.4	0.35	1.4	8.82	0.84	0.015
143.6	0.37	1.0	9.64	0.80	0.007
152.5	0.34	-1.45	13.46	0.76	-0.107
161.4	0.18	1.2	4.41	0.99	0.113
133.7	0.45	1.0	9.90	0.74	0.048

**Table 14.** Surplus production model estimates of fully-recruited biomass for Georges Bank 'a'. Posterior medians are labelled 0.5, columns labelled 0.025 and 0.975 are the lower and upper limits of the 95% credible regions.

Year	0.025	0.50	0.975
1981	5398.95	8036.50	15790.50
1982	2765.00	4896.50	11560.50
1983	2184.97	4025.00	9523.55
1984	2132.00	3854.00	8781.07
1985	3341.98	6155.00	14350.25
1986	5351.95	9910.00	23150.75
1987	5028.00	8663.00	20050.25
1988	3516.97	6284.50	14840.25
1989	3842.98	6823.00	15540.25
1990	4041.97	7086.00	16180.00
1991	4641.00	8055.50	18420.00
1992	5193.97	9365.00	22190.25
1993	4635.95	8315.00	19530.00
1994	3234.98	5780.50	13810.00
1995	2795.97	5266.50	12910.25
1996	4373.98	8400.50	19530.75
1997	4655.00	8770.00	20660.25
1998	3897.97	7341.00	17010.00
1999	5266.95	9955.00	23140.00
2000	12519.75	23320.00	53853.25
2001	11499.50	21925.00	52251.50
2002	12790.00	25310.00	59342.00
2003	7679.98	15100.00	37501.50
2004	5419.95	10680.00	25981.00
2005	5488.98	10660.00	25431.00
2006	7010.88	13250.00	30311.25
2007	9991.95	18790.00	42222.00

**Table 15.** Posterior probabilities of the posterior median exploitation rate  $\mu$  exceeding the provisional reference exploitation level (0.17) for different catch levels. The percent change (%  $\Delta$ ) is the change in population biomass from 2007 to 2008.

Catch (t)	2008		
	$\Pr(\mu \geq 0.17)$	$\mu$	% $\Delta$
3500	0.15	0.113	4.34
4000	0.25	0.129	2.53
4500	0.35	0.147	-0.23
5000	0.45	0.162	-2.42
5500	0.55	0.178	-4.29
6000	0.65	0.196	-6.87
6500	0.71	0.212	-9.14

**Table 16.** Posterior probabilities of a decline in biomass  $\Pr(\Delta < 0)$  from 2007 to 2008, for harvest levels spanning the range of historical landings (1981-2007). The corresponding posterior median exploitation rate  $\mu$  and percent change %  $\Delta$  in fully-recruited biomass associated with harvest levels are also provided.

Catch (t)	2008		
	$\mu$	$\Pr(\Delta < 0)$	% $\Delta$
1500	0.049	0.357	13.10
2000	0.065	0.389	9.62
2500	0.082	0.407	8.42
3000	0.098	0.425	7.11
3500	0.114	0.452	3.91
4000	0.131	0.478	1.92
4500	0.148	0.503	-0.22
5000	0.164	0.530	-2.51
5500	0.180	0.549	-4.11
6000	0.198	0.586	-7.18
6500	0.214	0.601	-8.97
7000	0.231	0.627	-10.32

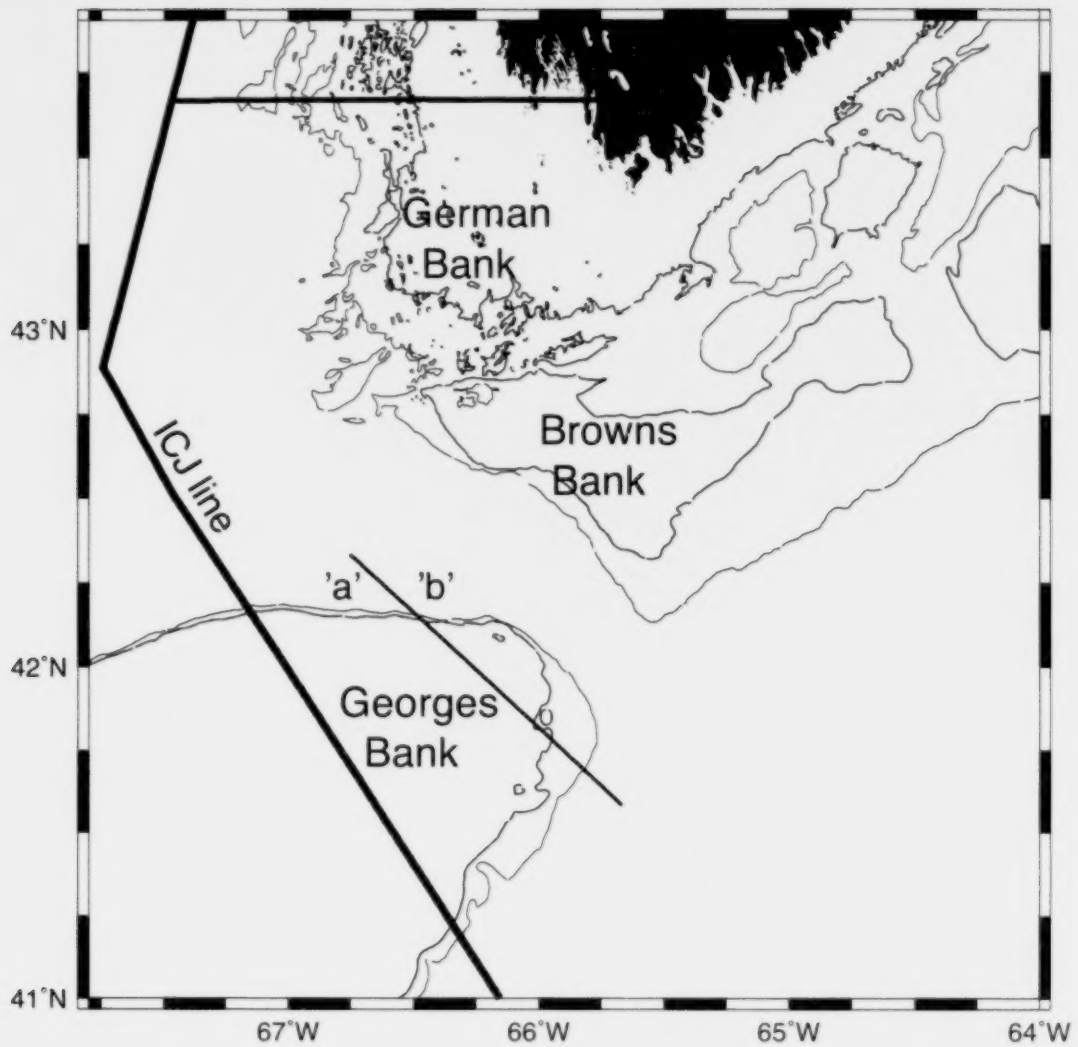
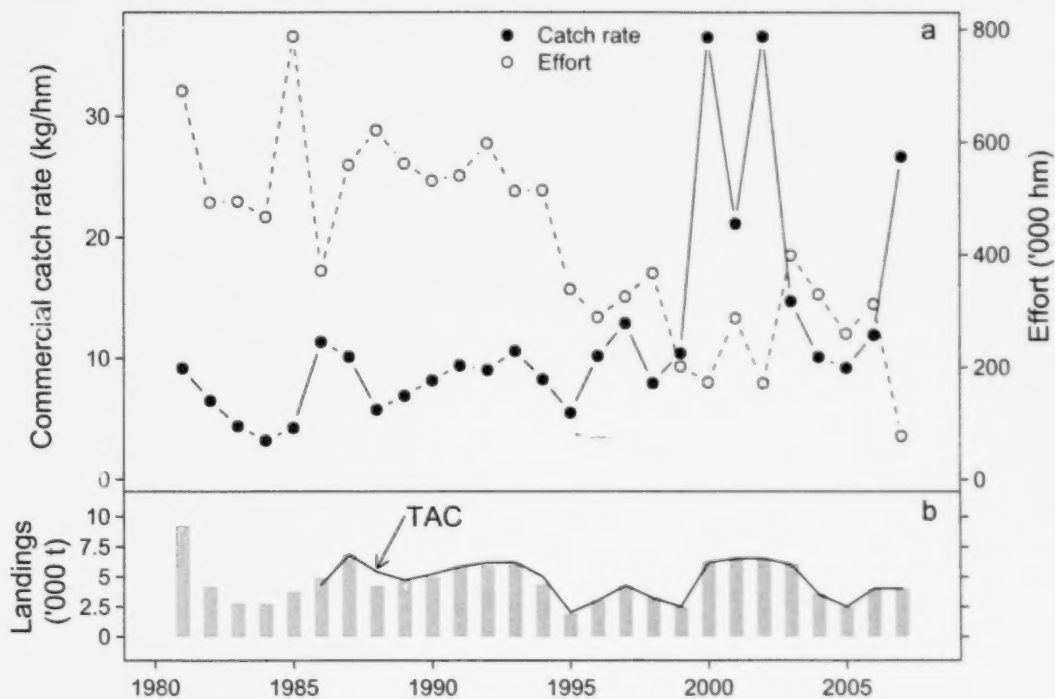
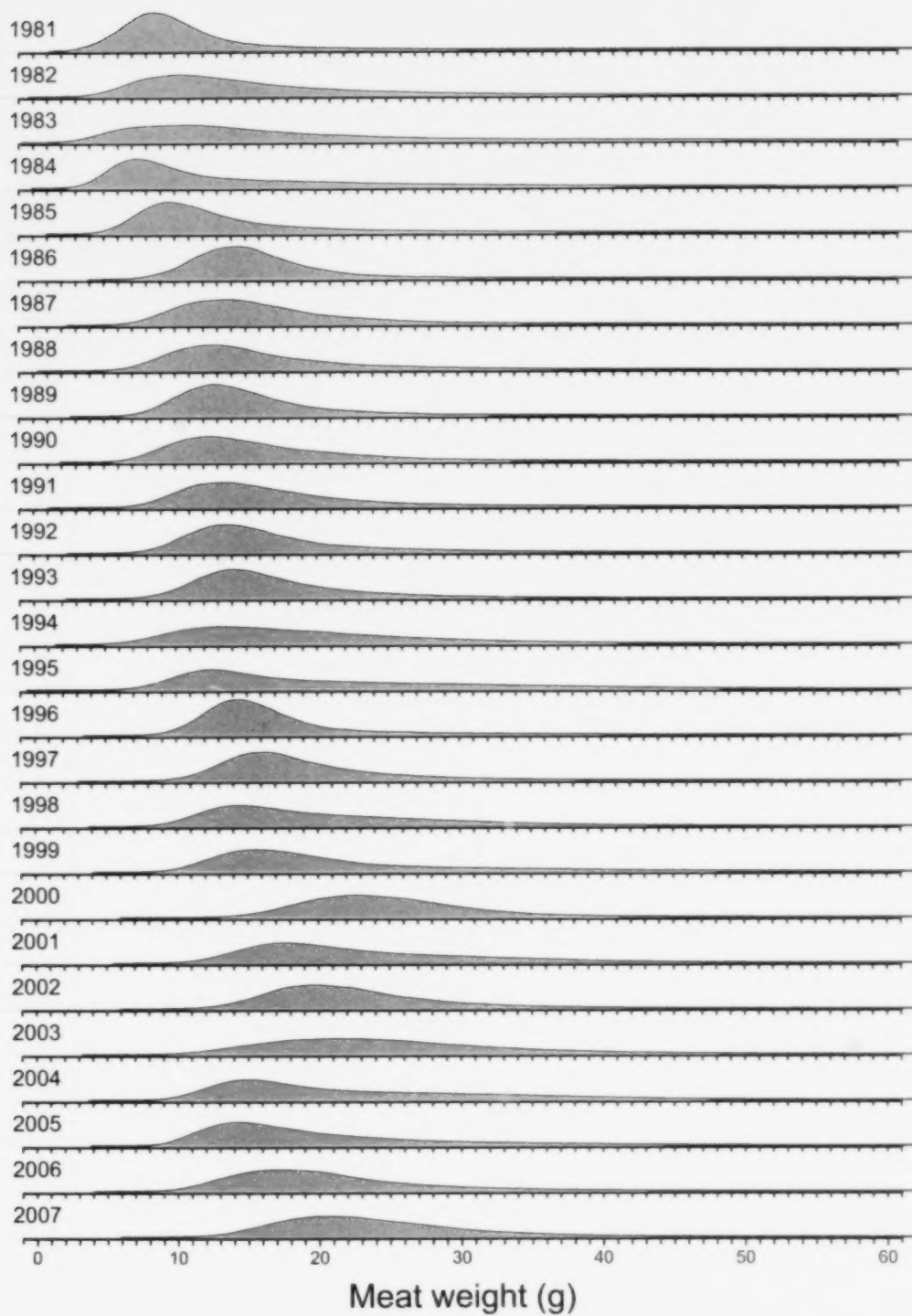


Figure 1. Map of Georges Bank.

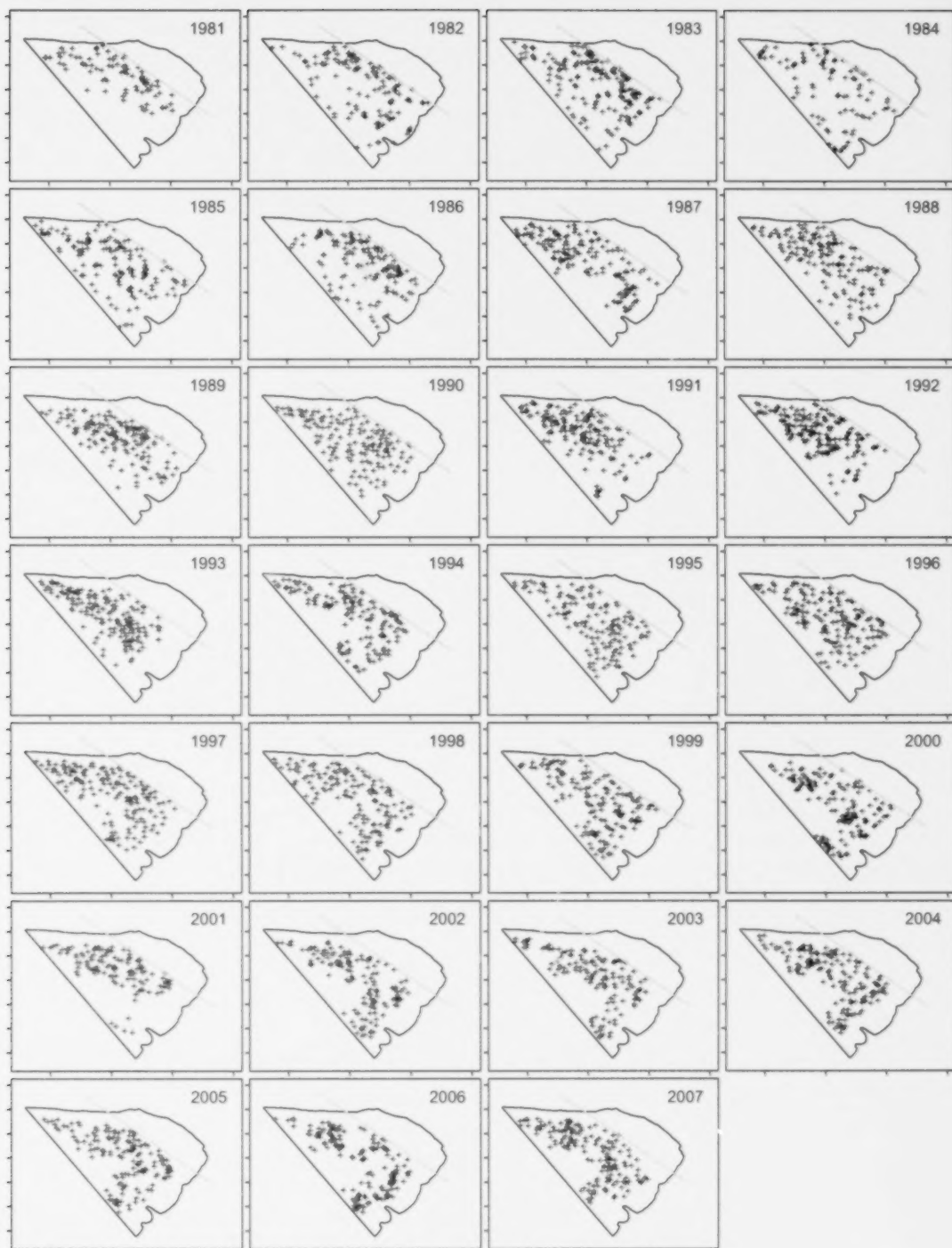


**Figure 2.** Commercial catch rate (kg/hm), effort ('000 hm) (a), landings and TAC (b) for the scallop fleet on Georges Bank 'a'. Catch rate and effort values for 2007 have been adjusted to exclude fishing inside a voluntary seedbox closure that was opened at the start of 2007. Total allowable catches prior to 1998 are for Georges Bank in its entirety.

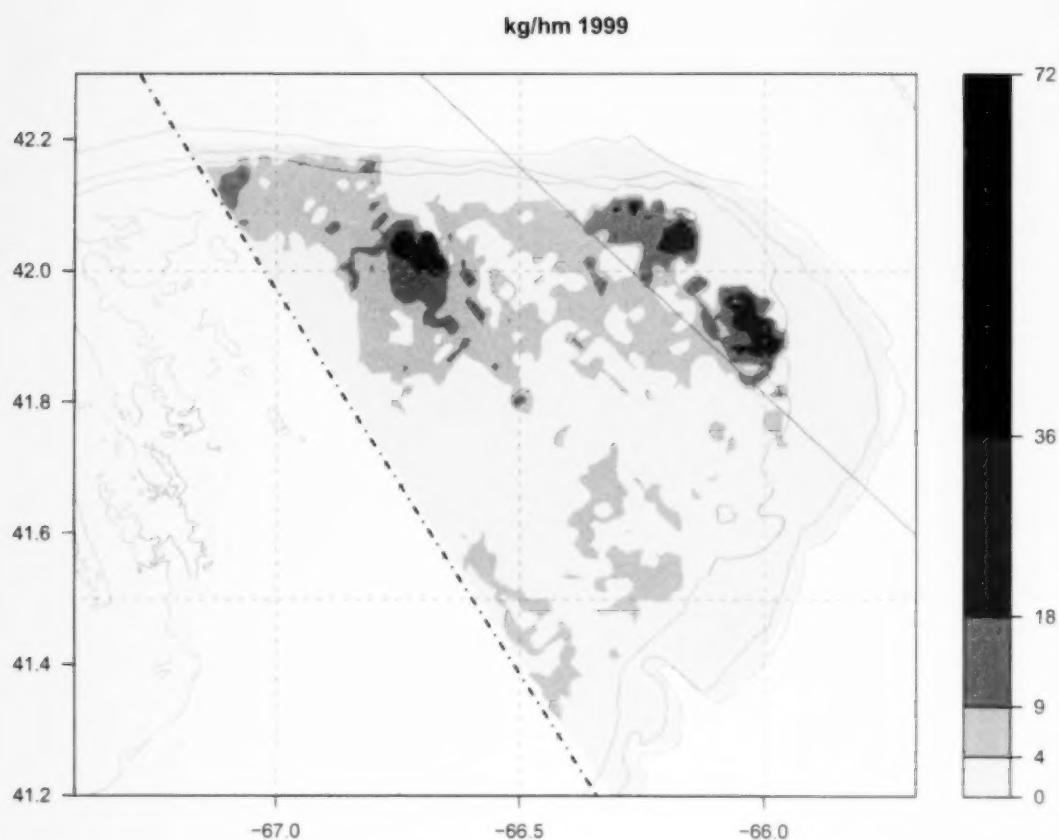


**Figure 3.** Annual meat weight distributions from commercial samples.



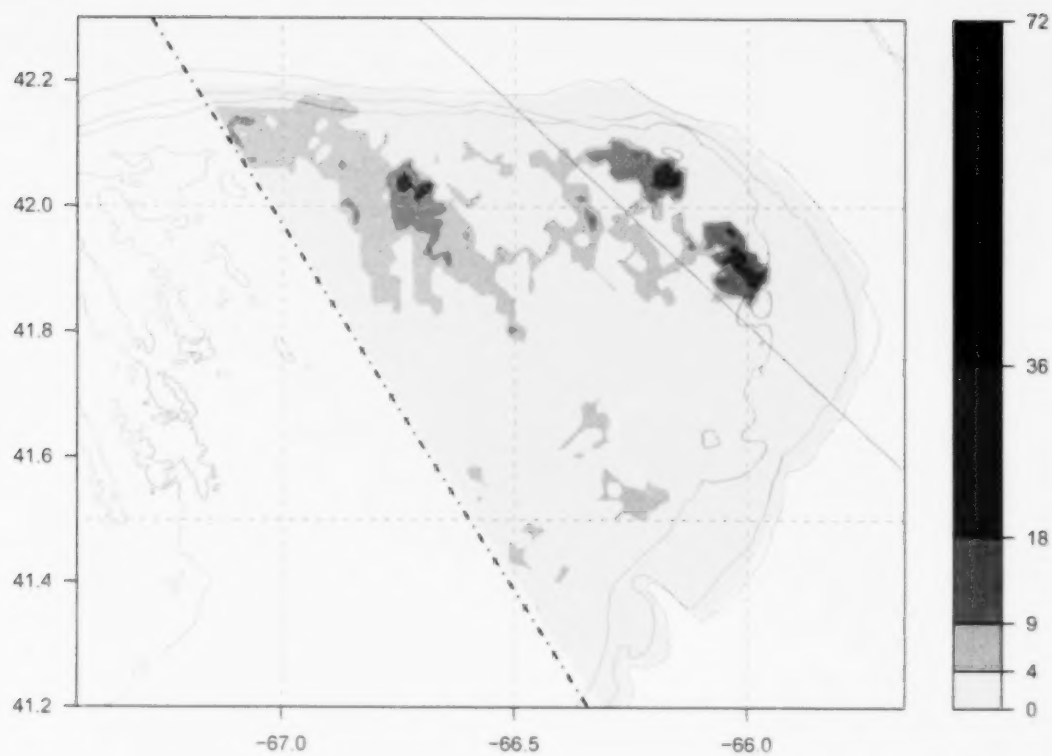


**Figure 4.** Positions of survey tows on Georges Bank 'a' from 1981 to 2007.

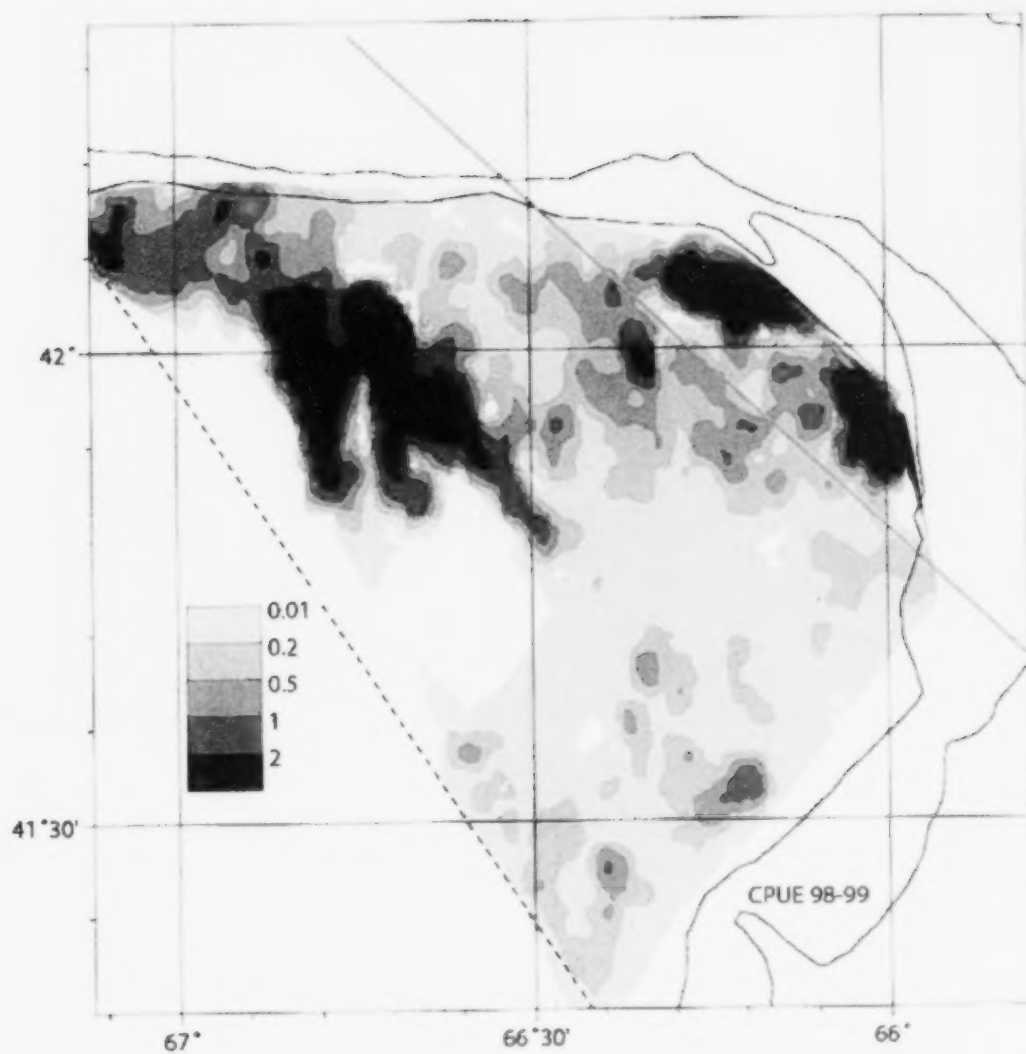


**Figure 5.** Smoothed and spatially interpolated commercial catch rate strata for Georges Bank 'a' based on commercial catch rates from September 1998 to June 1999. The catch rate strata are displayed in the scale on the right.

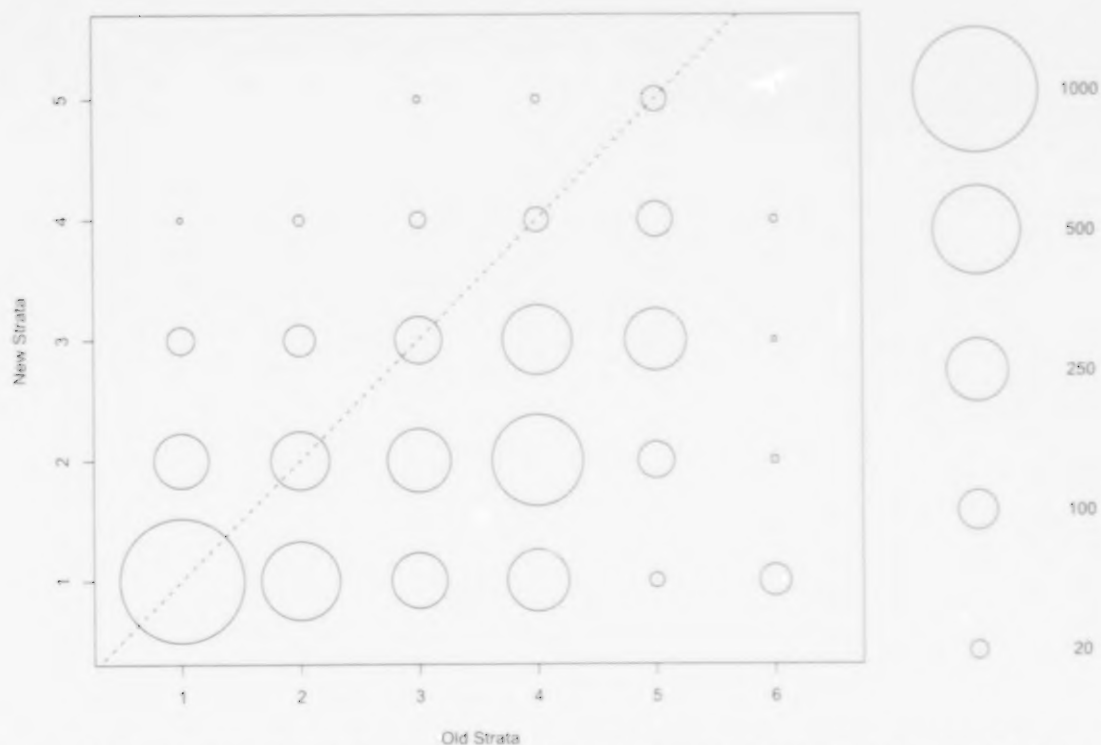
CPUE (kg/hm) 1998 - 1999



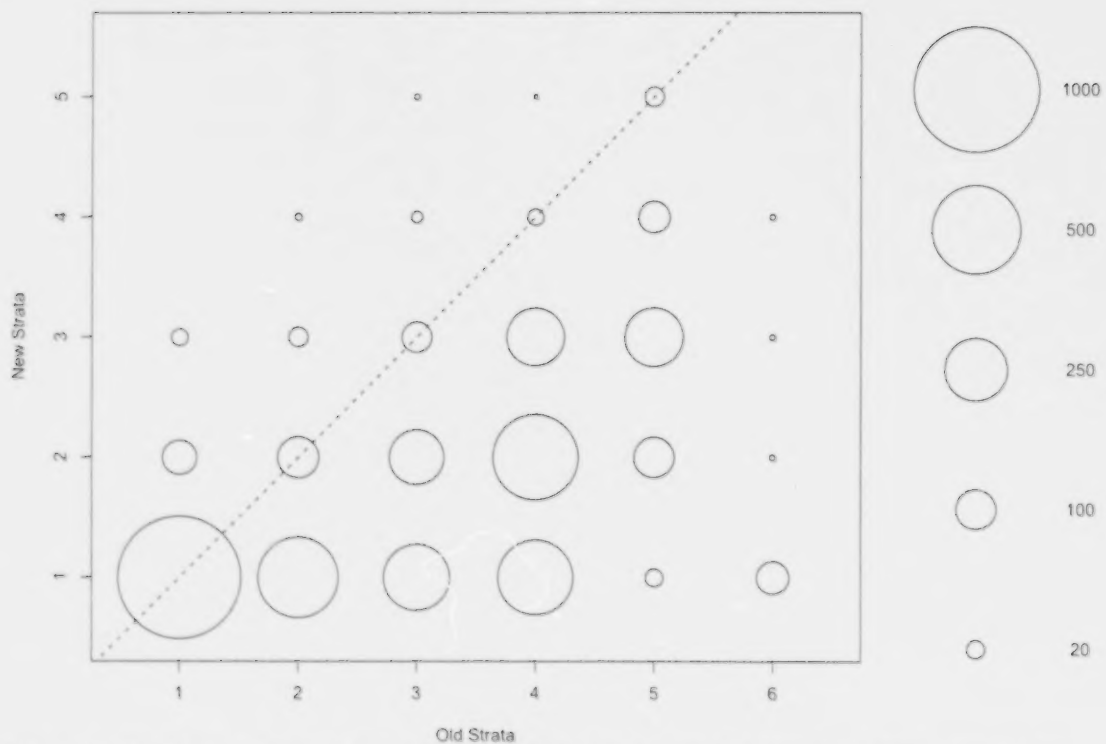
**Figure 6.** Smoothed and spatially interpolated commercial catch rate strata for Georges Bank 'a' based on commercial catch rates from September 1998 to June 1999. The catch rate strata are displayed in the scale on the right.



**Figure 7.** Commercial catch rate interpolation for the 1999 Georges Bank survey, from Fig. 9, (Robert et al. 2000). The scale bar displays the 5 catch rate strata in kg/crh.

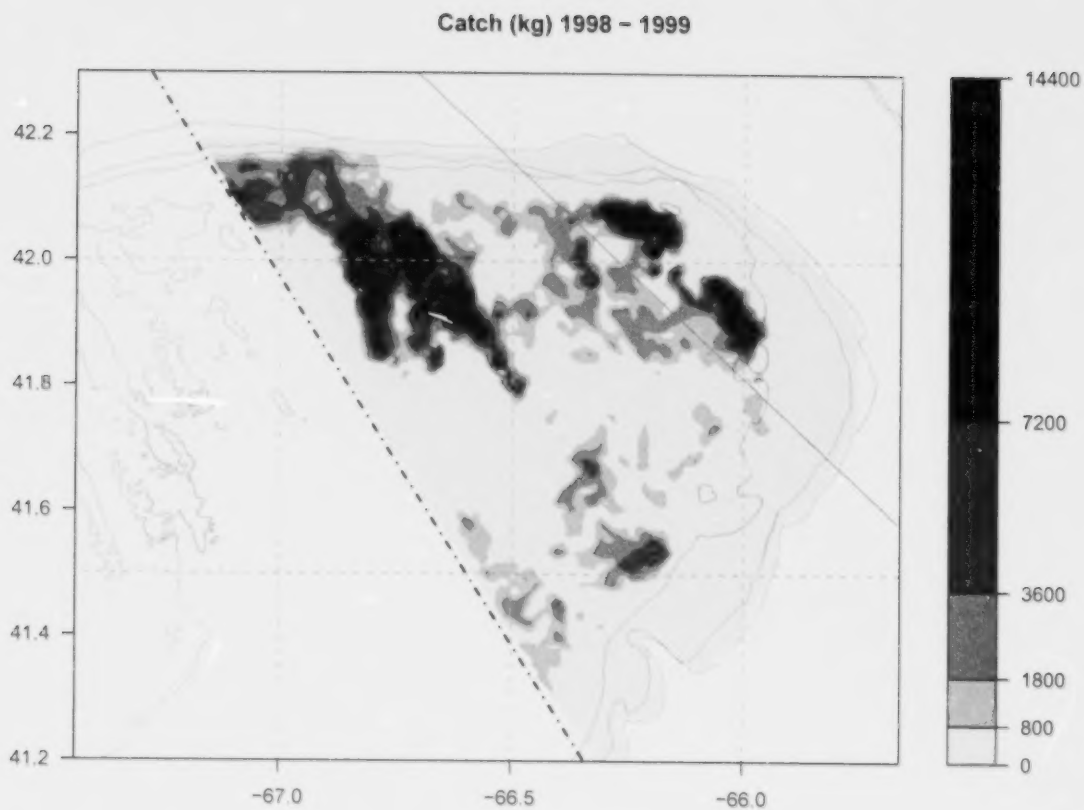


**Figure 8.** Comparison of original strata membership (Old Strata) and new strata membership after post-stratification based on average catch rates. All survey tows from 1981-2007 are included. The symbol size is proportion to the number of tows in each strata combination.

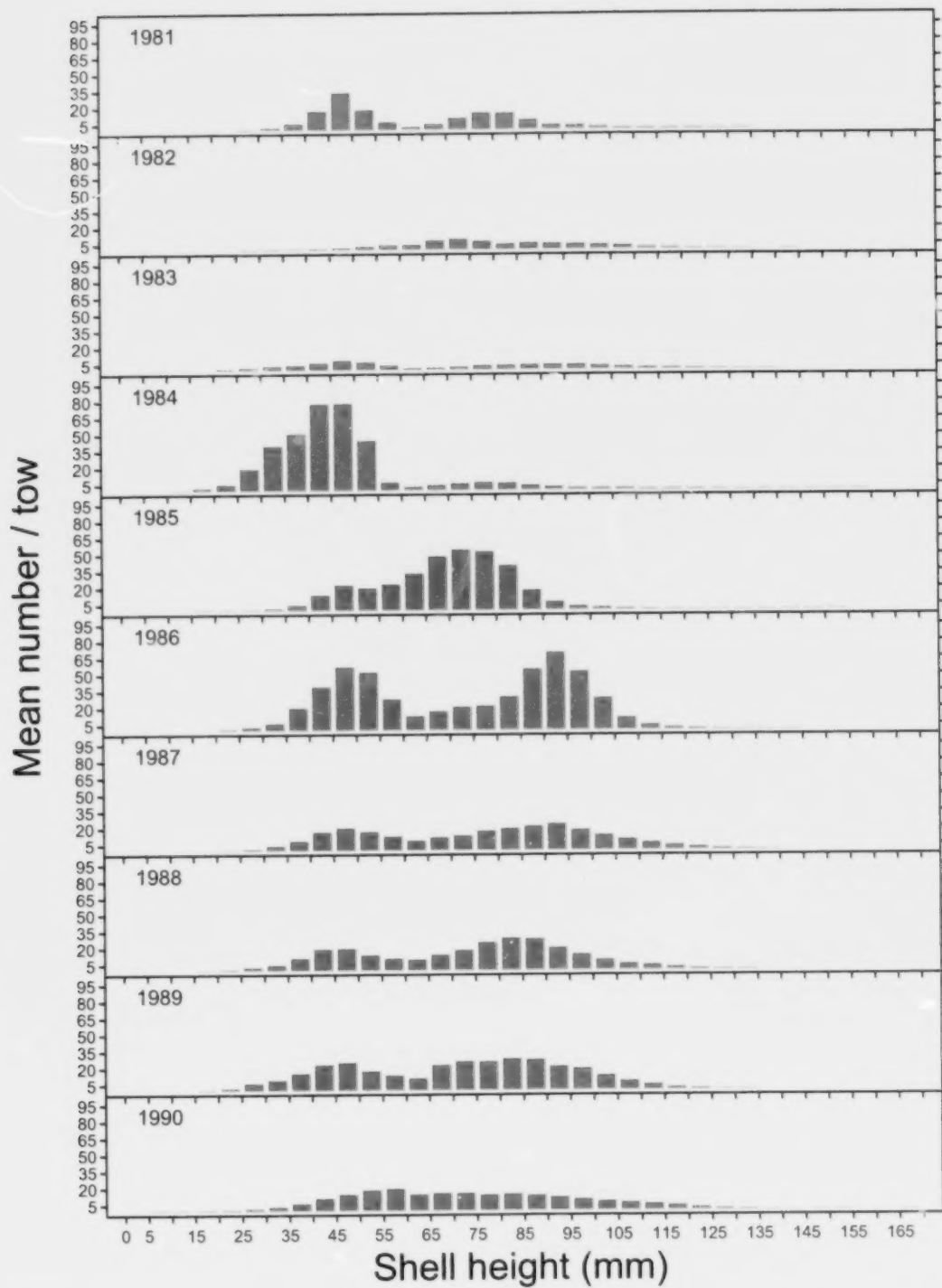


**Figure 9.** Comparison of original strata membership (Old Strata) and new strata membership after post-stratification based on catch rates obtained with the jackknife estimator. All survey tows from 1981-2007 are included. The symbol size is proportion to the number of tows in each strata combination.

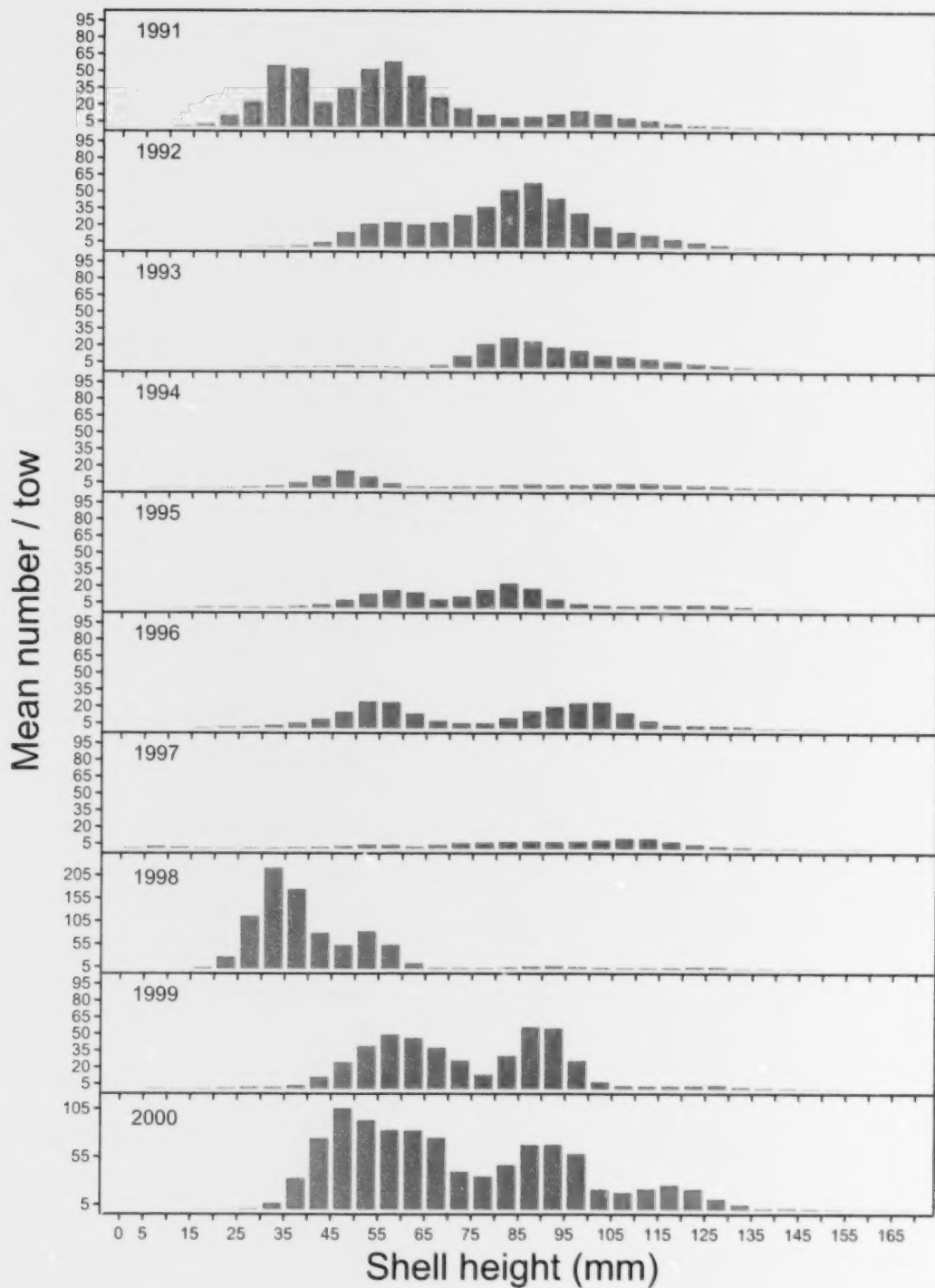




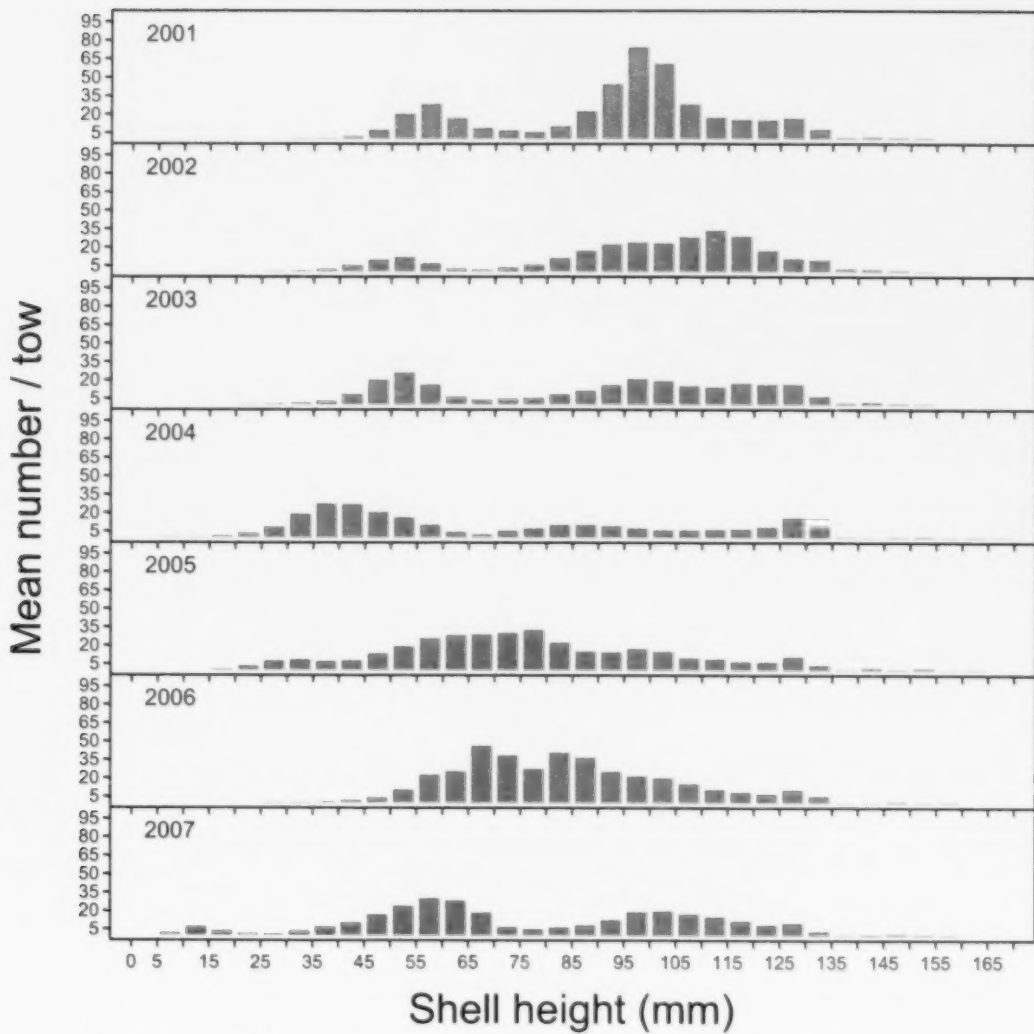
**Figure 10.** Smoothed and spatially interpolated commercial catch countours for Georges Bank 'a' based on commercial catch data from September 1998 to June 1999. The catch levels in kg are displayed in the scale on the right.



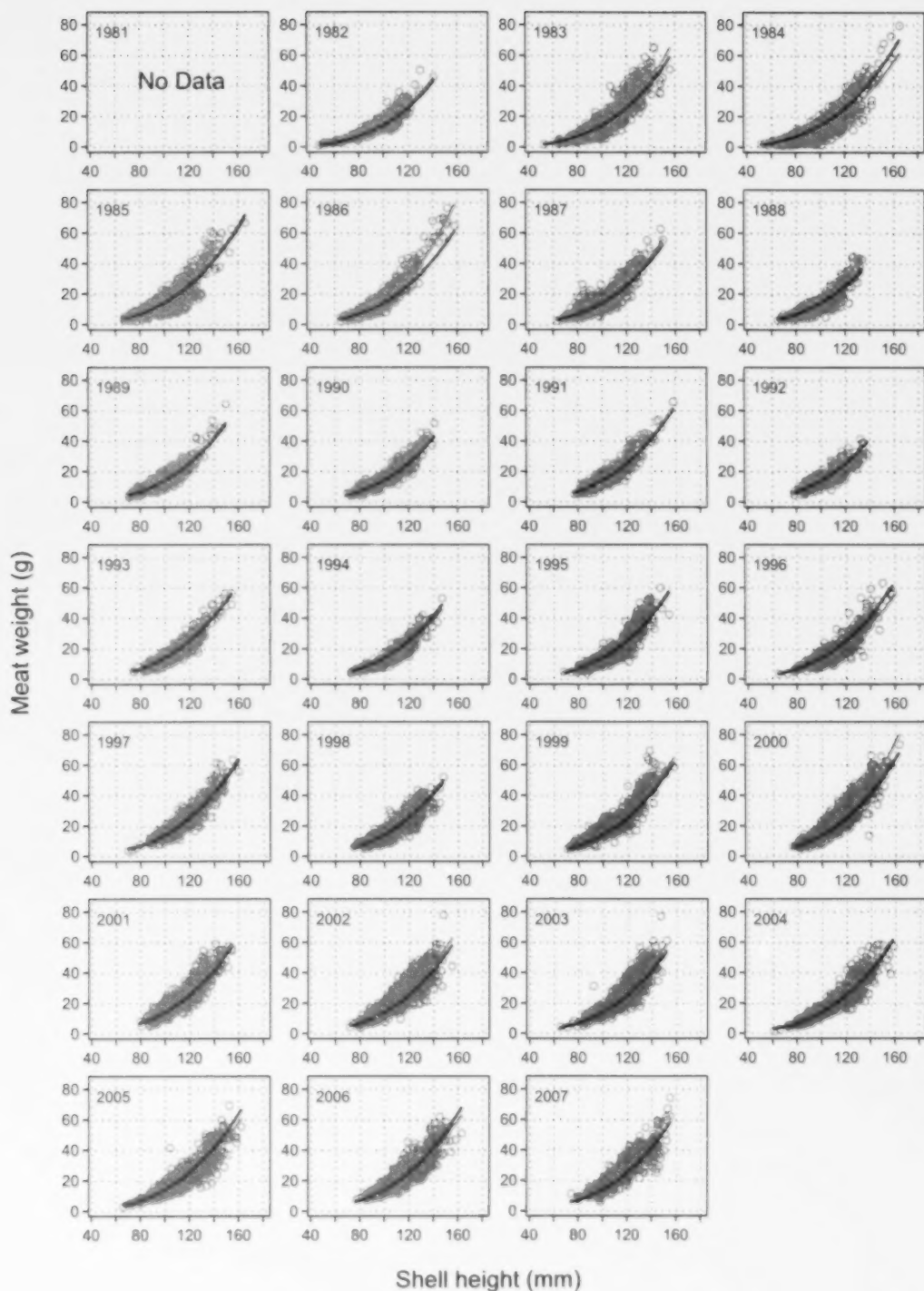
**Figure 11.** Shell height frequencies for mean number per tow from the August survey on Georges Bank 'a'. 1981-1990



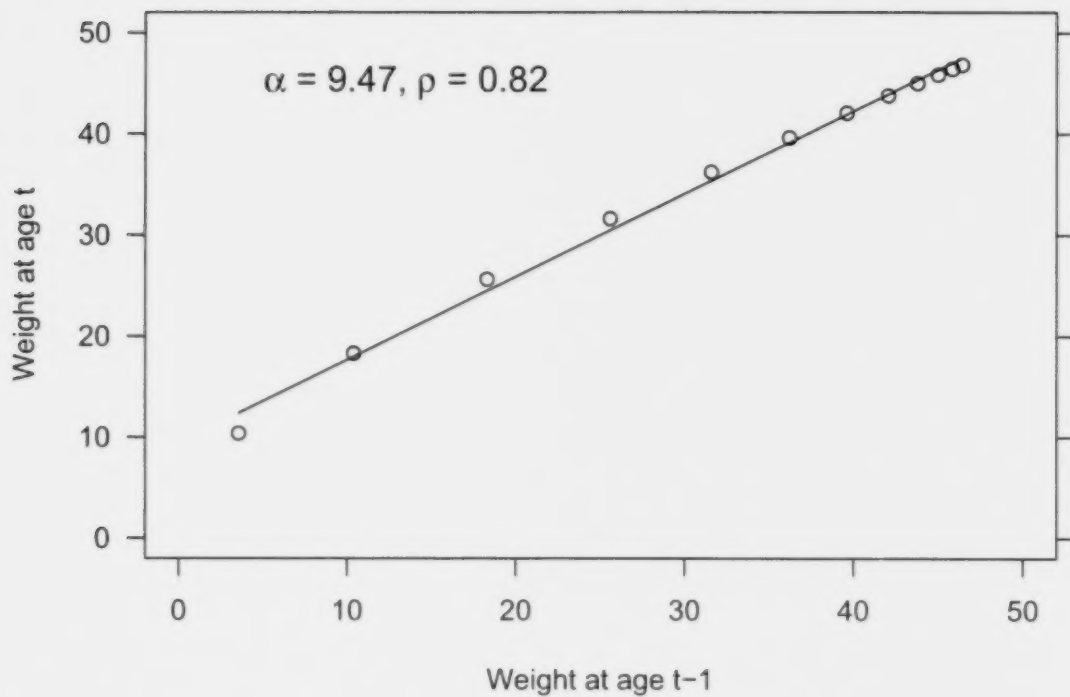
**Figure 12.** Shell height frequencies for mean number per tow from the August survey on Georges Bank 'a' 1991-2000. Note the different y-axis scales used in 1998 and 2000.



**Figure 13.** Shell height frequencies for mean number per tow from the August survey on Georges Bank 'a'. 2001-2007

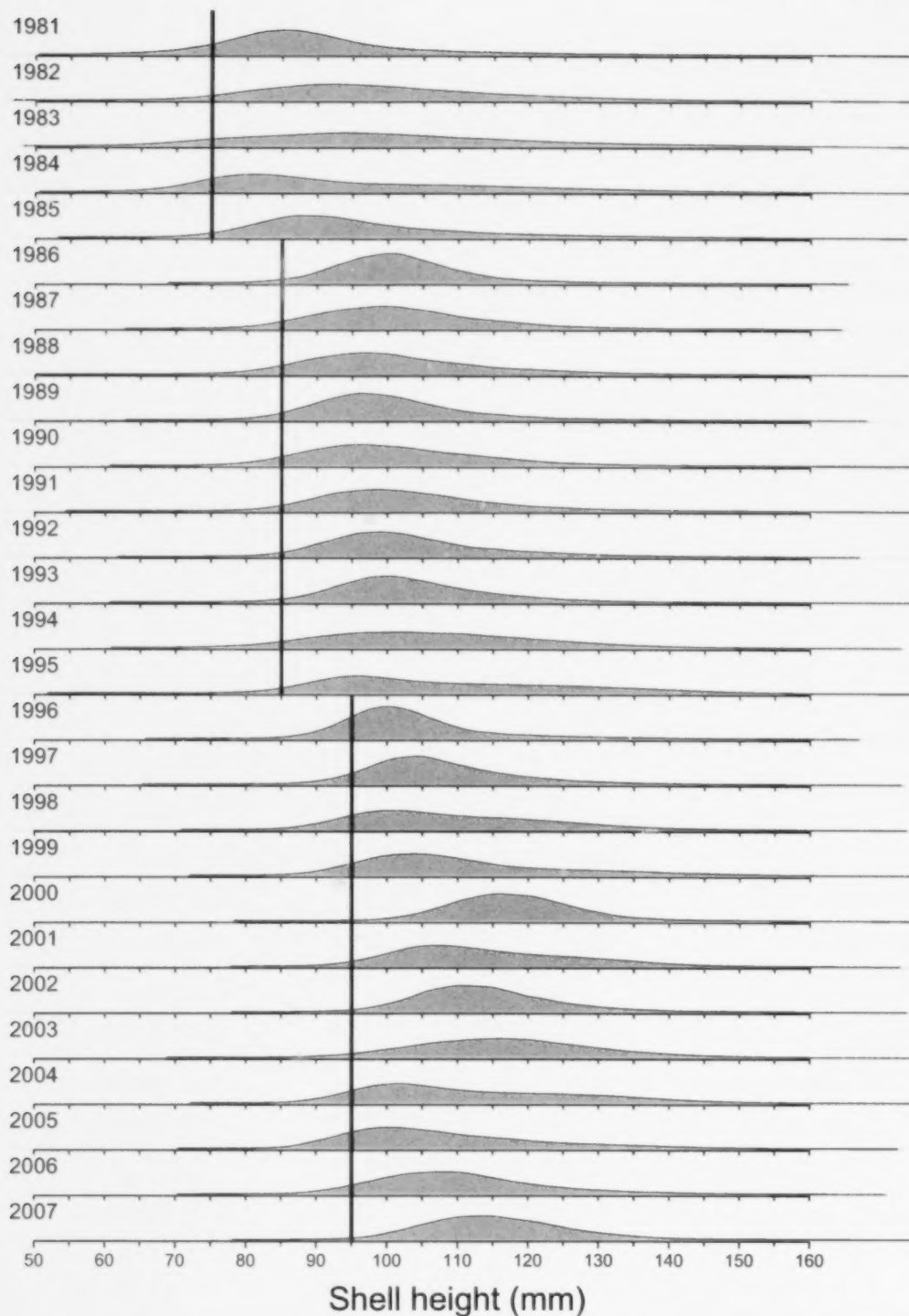


**Figure 14.** Meat weight - shell height relationship by year from annual research survey samples taken on Georges Bank 'a'. Regression lines are from a linear mixed effects model with shell height as a random effect and year as a grouping variable. The blue line in each panel is the fixed effects relationship and the red lines are the random effects relationships for each year.

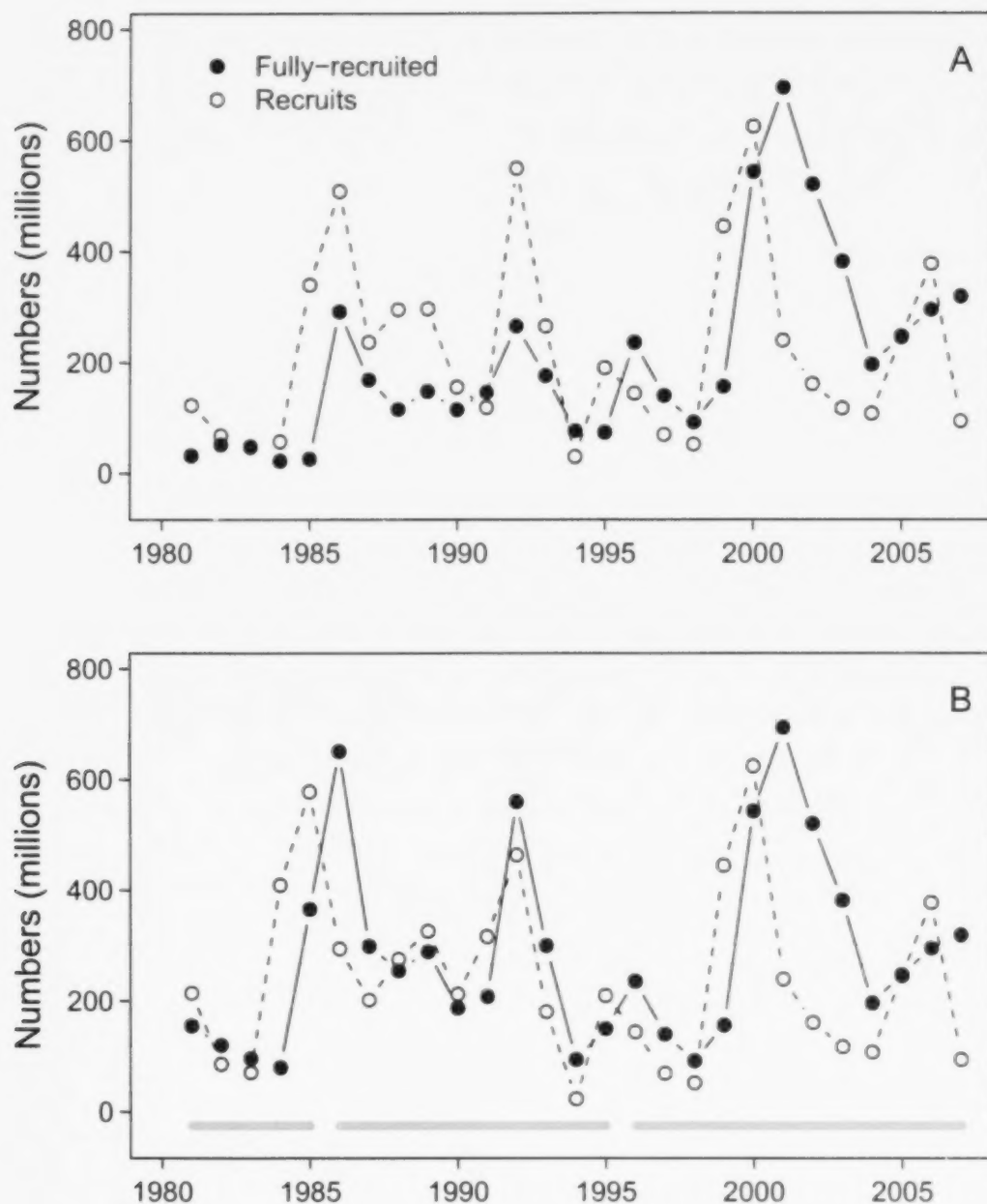


**Figure 15.** Weight at age relationship for scallops on Georges Bank 'a'. Slope ( $\rho$ ) and intercept ( $\alpha$ ) estimates are given. The regression is fit to age 3+ scallops.

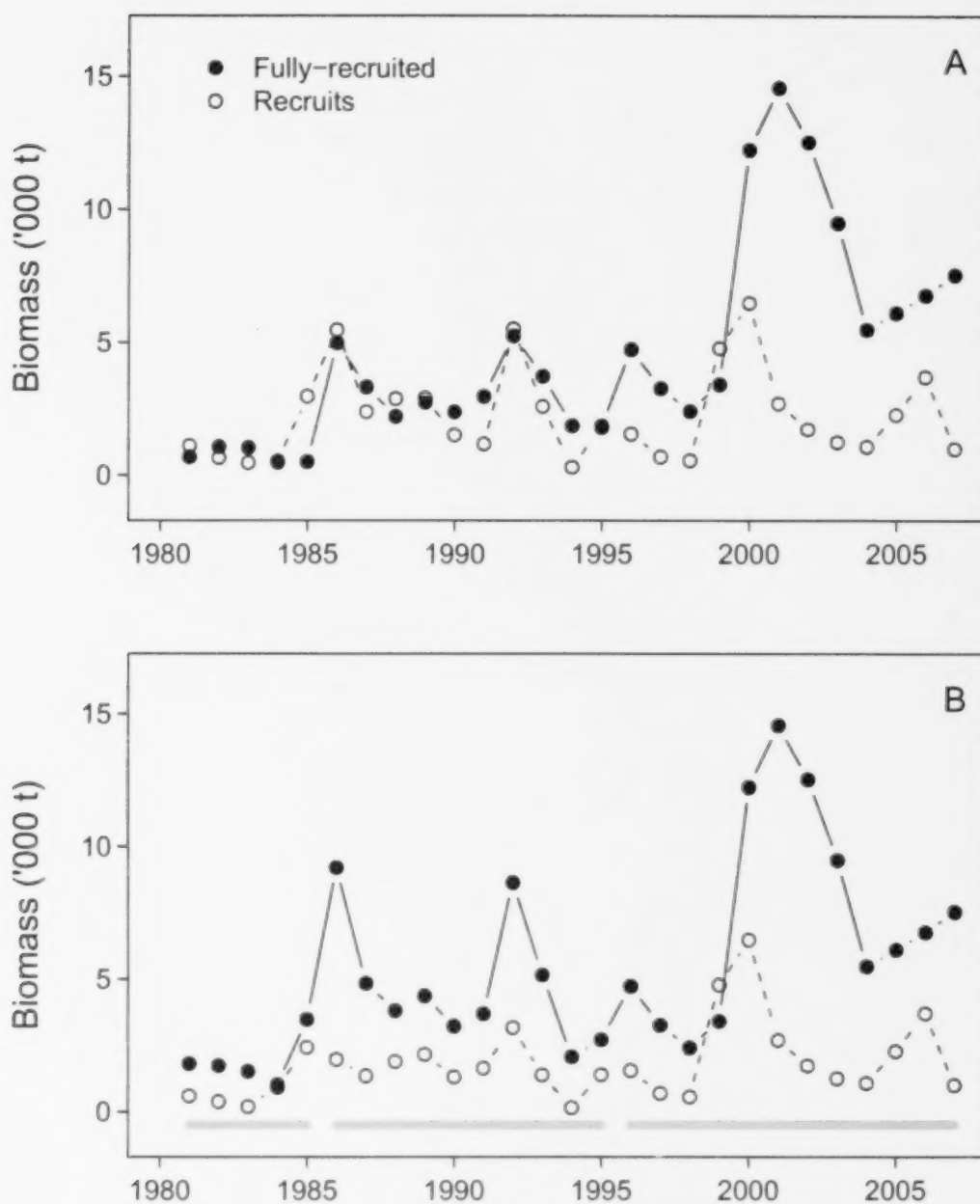




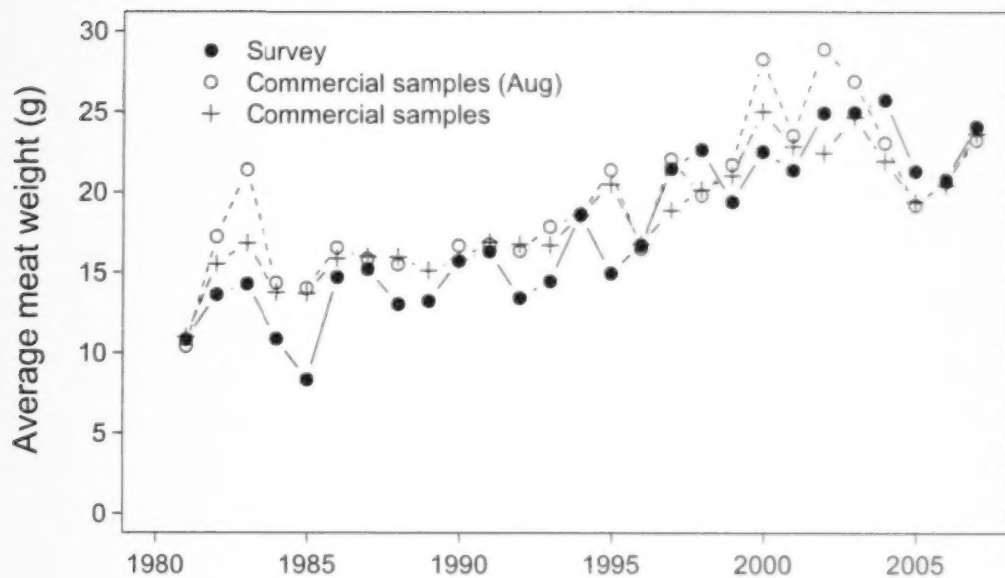
**Figure 16.** Annual shell height distributions in landings, from commercial samples. Vertical lines display 3 distinct phases of size at recruitment to fishery: > 75 mm in 1981-1985; > 85 mm in 1986-1995; > 95 mm in 1996-2007. Shell heights were converted from sampled meat weights using the annual shell height - meat weight relationships from the August survey (Figure 14).



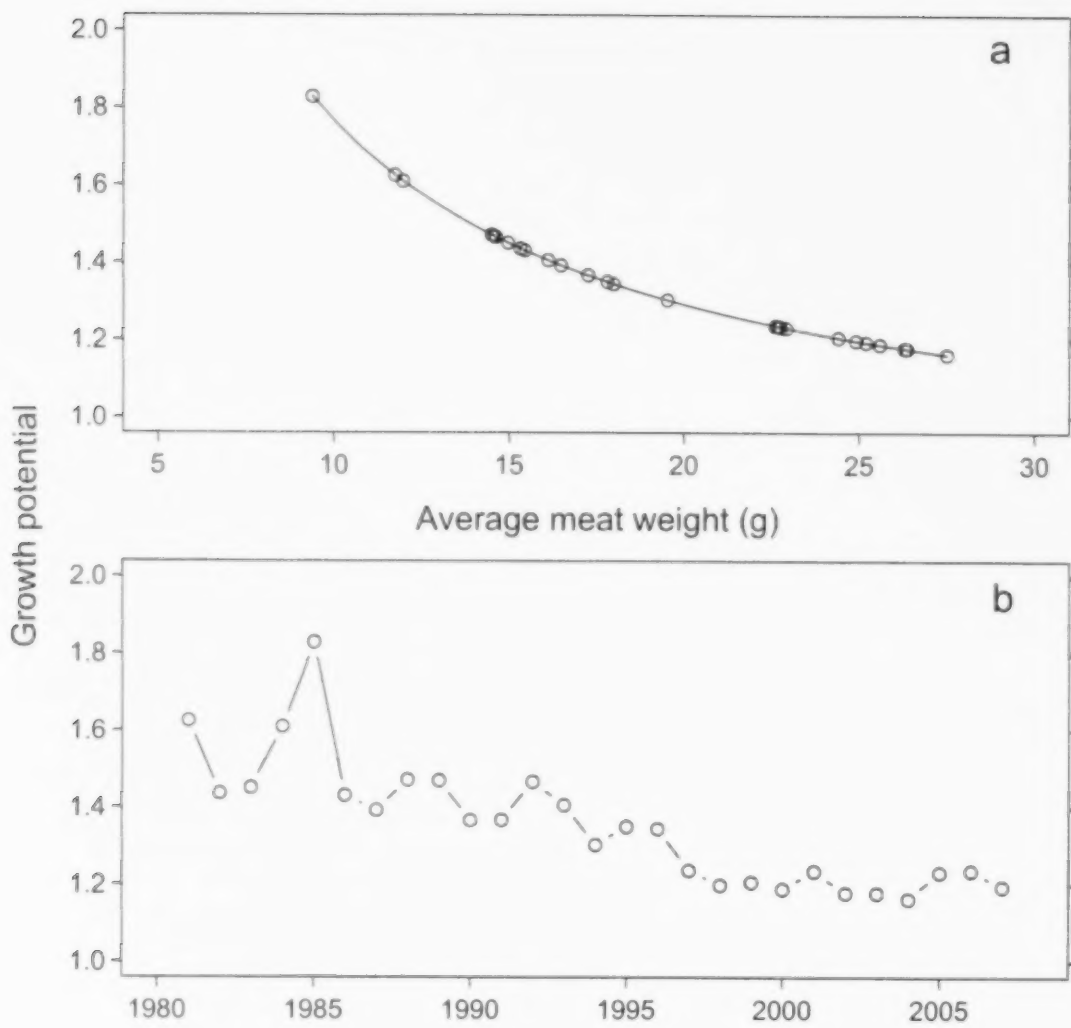
**Figure 17.** Trends in survey estimates of total numbers of commercial and recruit size scallops from the August survey of Georges Bank 'a'. (A) Fully-recruited is defined as a constant  $> 95$  mm and recruit size is defined as a constant 76-95 mm. (B) Fully-recruited is defined as  $> 75$  mm (1981-1985),  $> 85$  mm (1986-1995) and  $> 95$  mm (1996-2007). Recruit size is defined as 45-75 mm (1981-1985), 65-85 mm (1986-1995) and 75-95 mm (1996-2007). The grey lines at bottom of panel B indicate the three periods of differing size at recruitment to the fishery. Survey estimates are not corrected for dredge efficiency or size-selectivity.



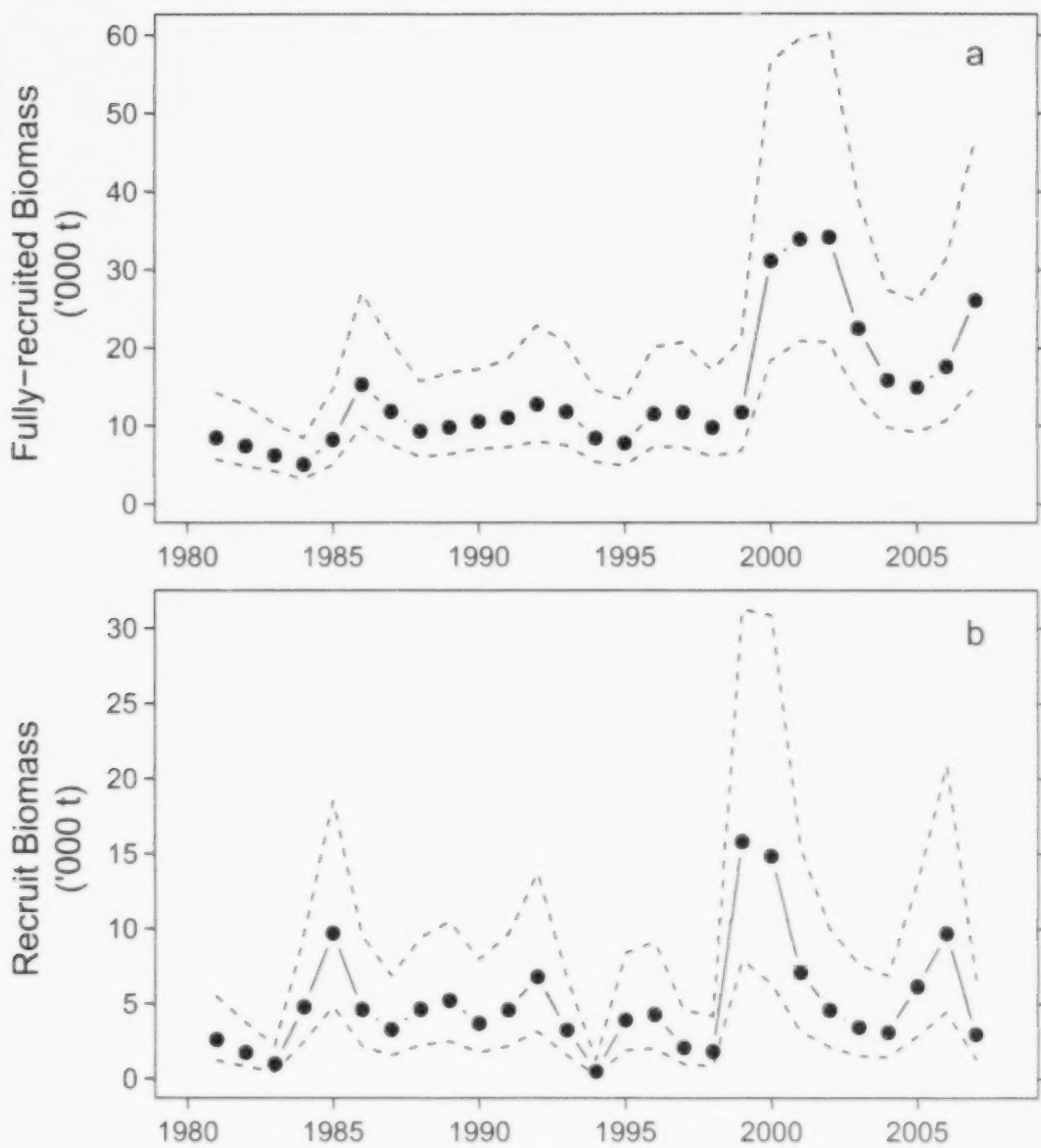
**Figure 18.** Trends in survey estimates of total biomass of commercial and recruit size scallops from the August survey of Georges Bank 'a'. (A) Fully-recruited is defined as a constant > 95 mm and recruit size is defined as a constant 76-95 mm. (B) Fully-recruited is defined as > 75 mm (1981-1985), > 85 mm (1986-1995) and > 95 mm (1996-2007). Recruit size is defined as 45-75 mm (1981-1985), 65-85 mm (1986-1995) and 75-95 mm (1996-2007). The grey lines at bottom of panel B indicate the three periods of differing size at recruitment to the fishery. Survey estimates are not corrected for dredge efficiency or size-selectivity.



**Figure 19.** Trends in average meat weight of fully-recruited scallops from the August survey of Georges Bank 'a' and from commercial samples taken in August and throughout the year. Average meat weights were estimated assuming the 3-phase pattern in size at recruitment (see *Size at Recruitment to Fishery*).

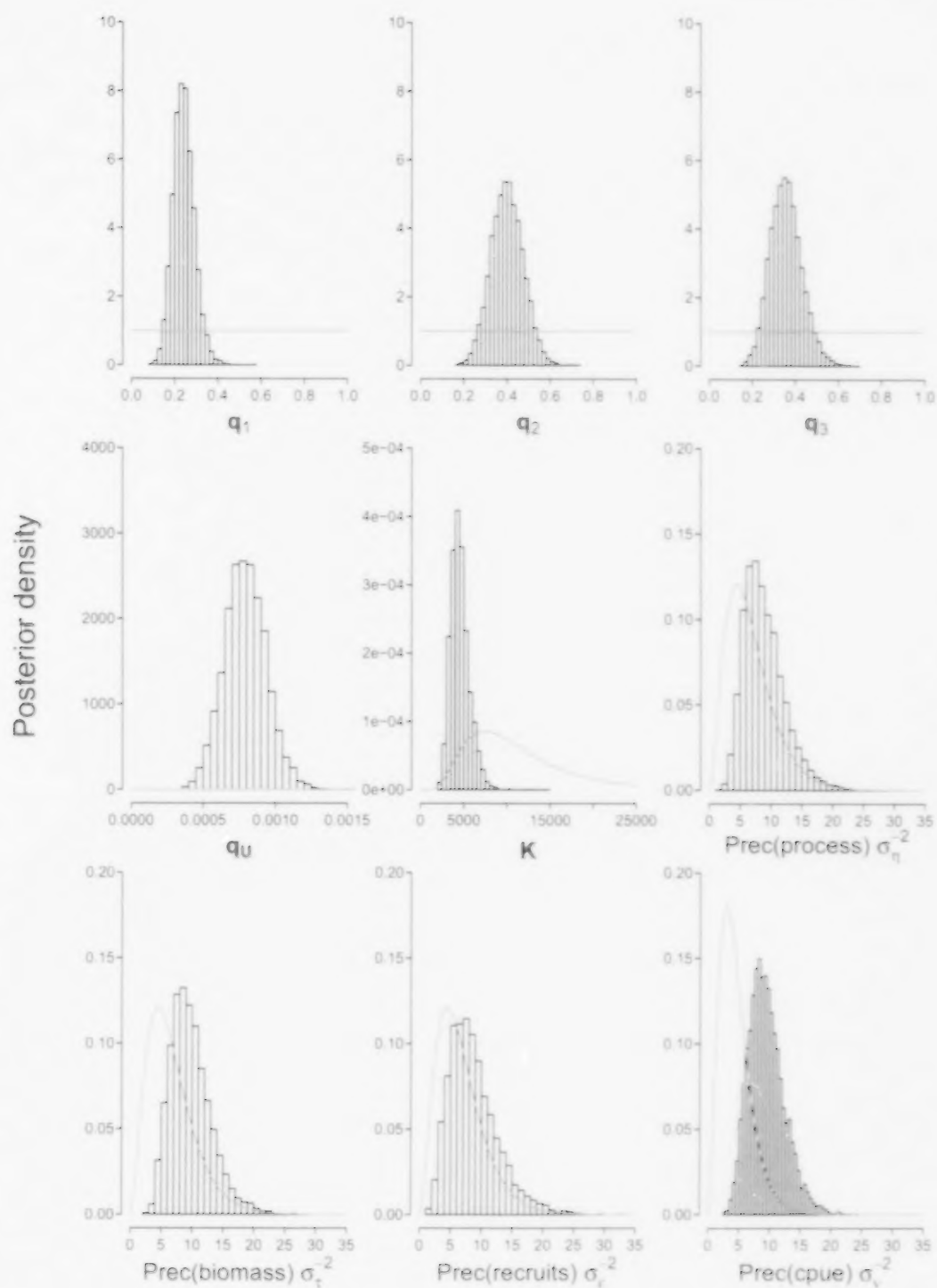


**Figure 20.** Growth potential as a function of (a) average scallop meat weight and (b) year for the Georges Bank 'a' stock.

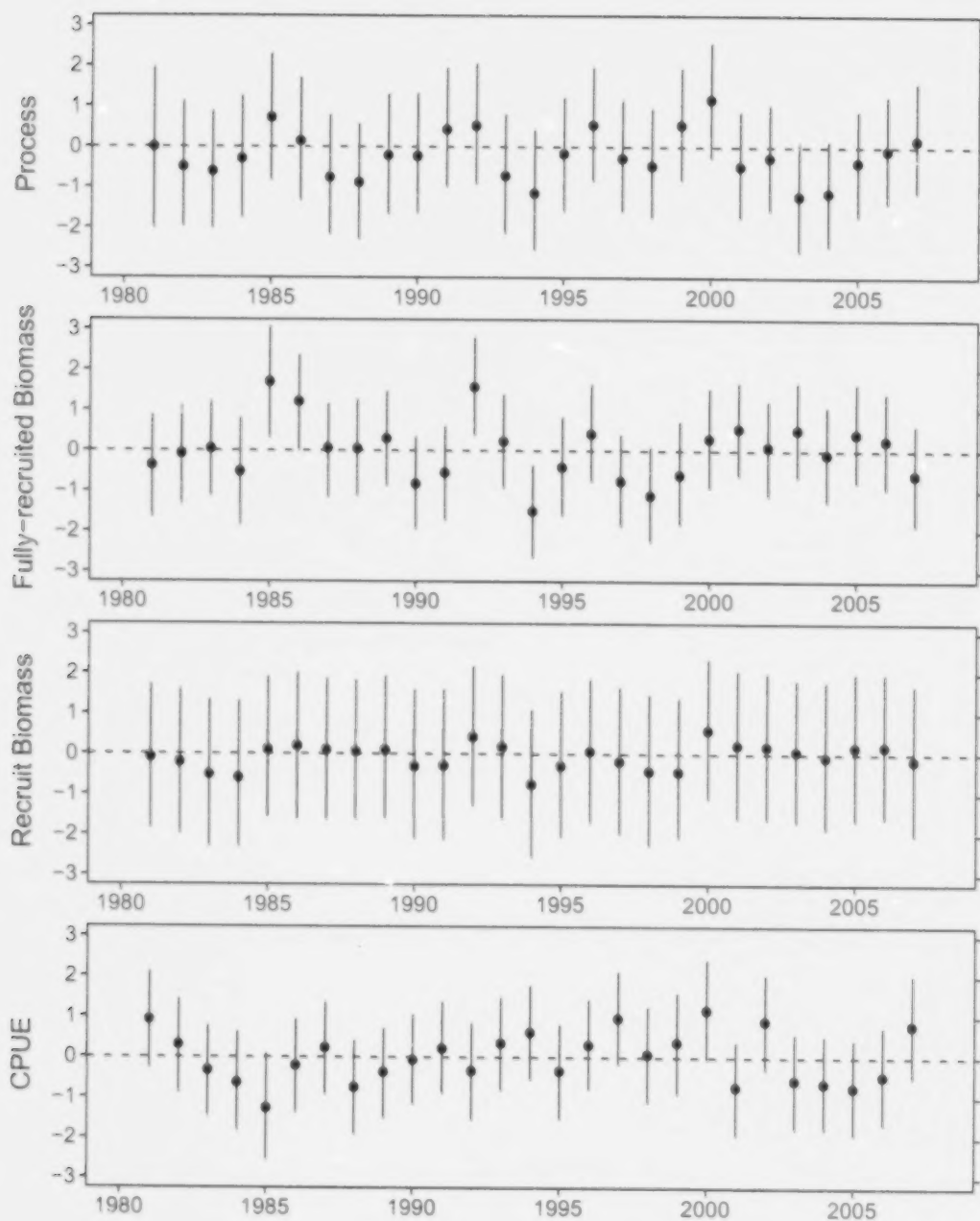


**Figure 21.** Biomass estimates for (a) fully-recruited scallops and (b) recruits from the delay-difference model. Dashed lines are the upper and lower 95% credible limits.

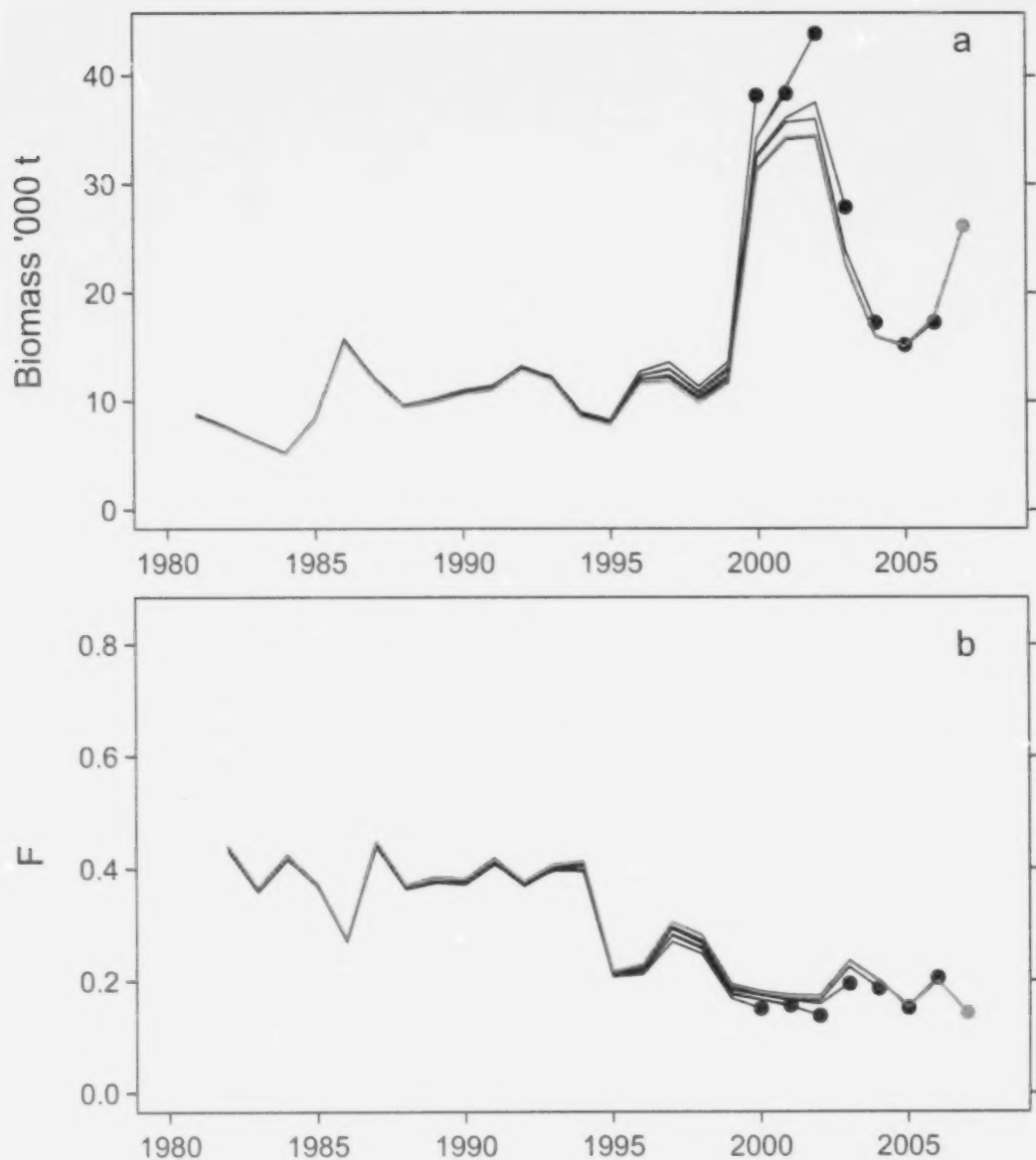




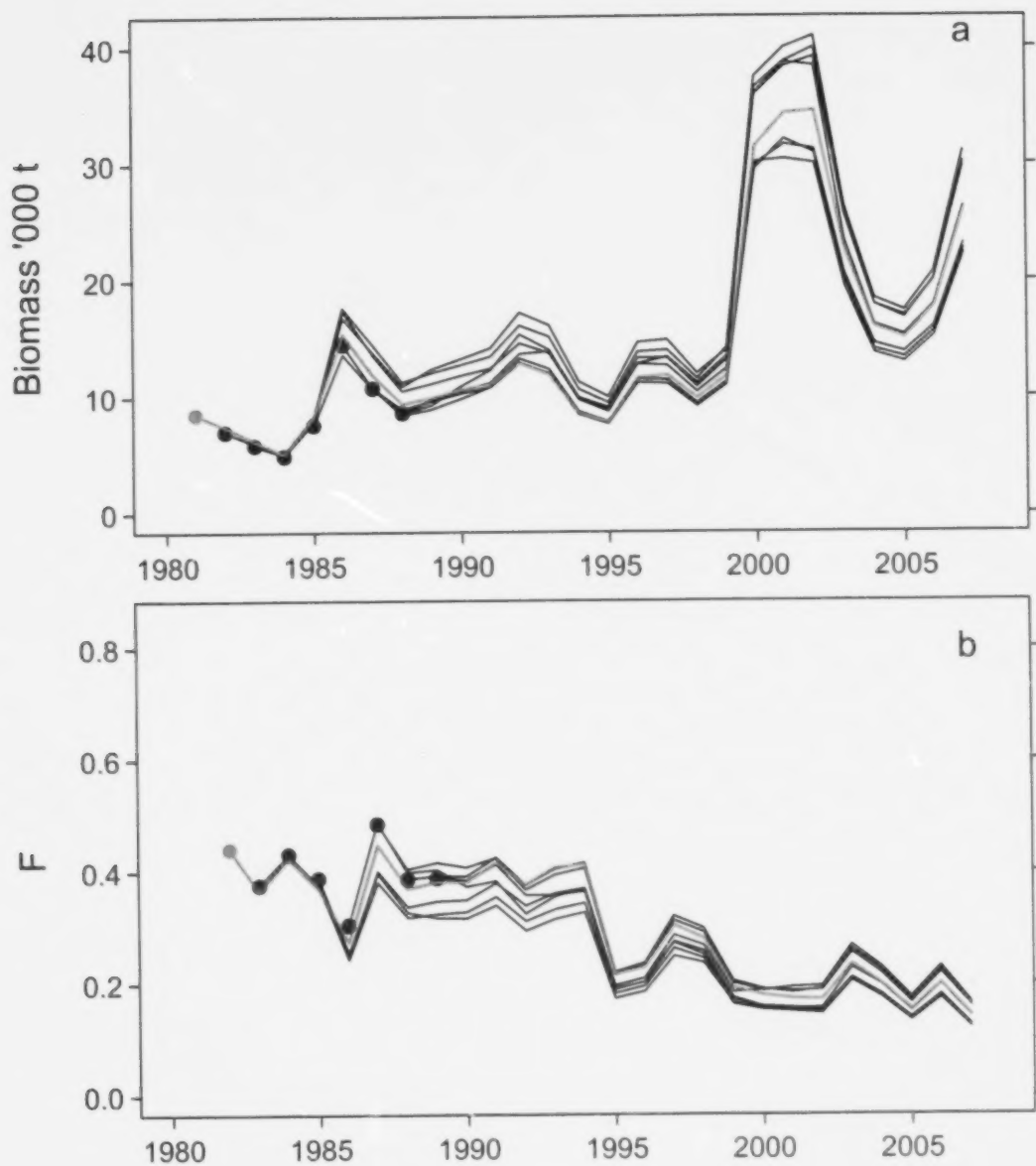
**Figure 22.** Posterior distributions for proportionality coefficients,  $K$ , and precision terms ( $1/\text{Var}$ ) in the delay-difference model. Solid red lines show the prior densities.



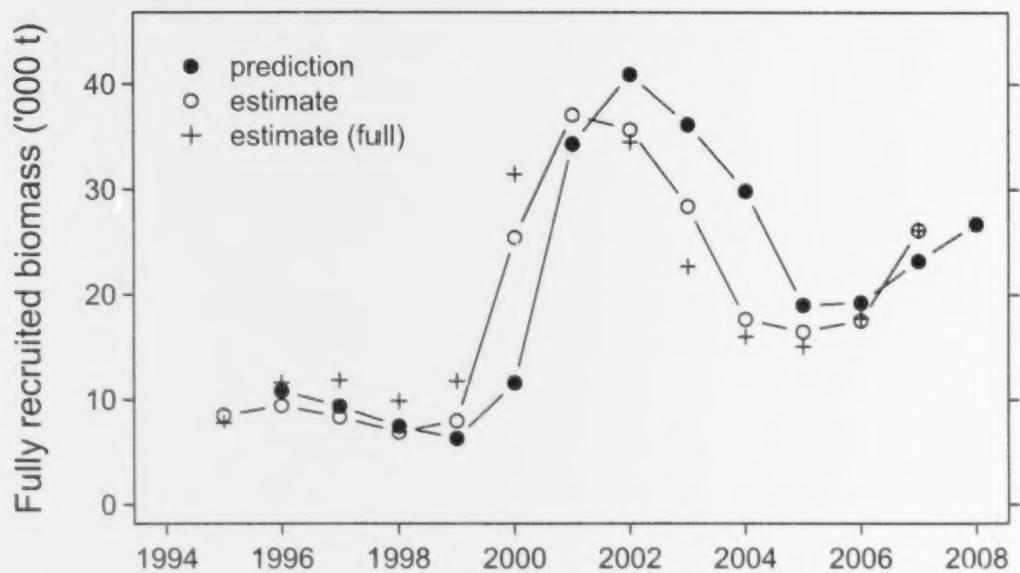
**Figure 23.** Residuals for the main components of the delay-difference model.



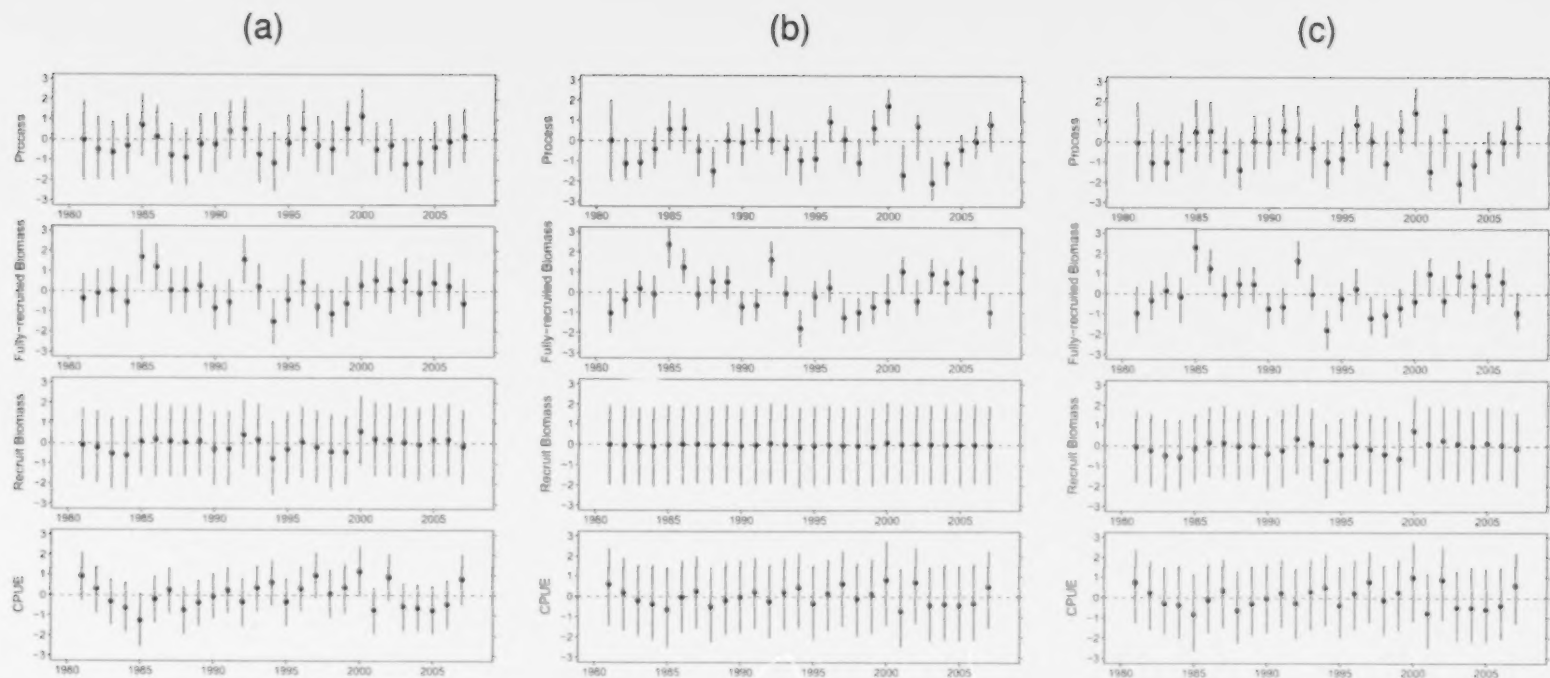
**Figure 24.** Retrospective plots for (a) biomass estimates and (b) fishing mortality from fits of the delay-difference model using time series up to 2002, 2003, 2004, 2005, 2006, or 2007. The red lines display the fit to the full time series.



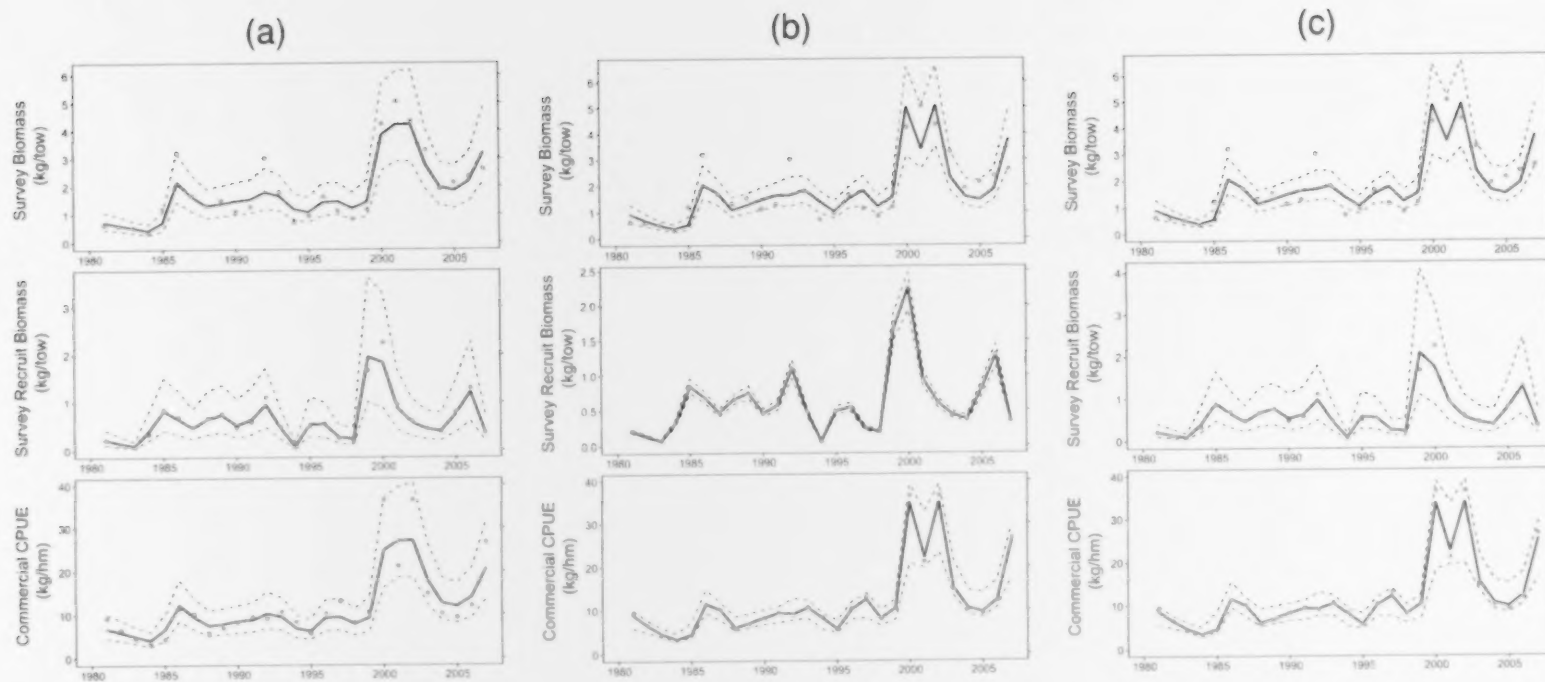
**Figure 25.** Prospective plots for (a) biomass estimates and (b) fishing mortality from fits of the delay-difference model using time series beginning in 1981, 1982, 1983, 1984, 1985, 1986, 1987 or 1988. The red lines display the fit to the full time series.



**Figure 26.** Comparison of predicted and estimated biomass from the delay-difference model. Biomass estimates using data only up to each year and the full time series (+) are presented.

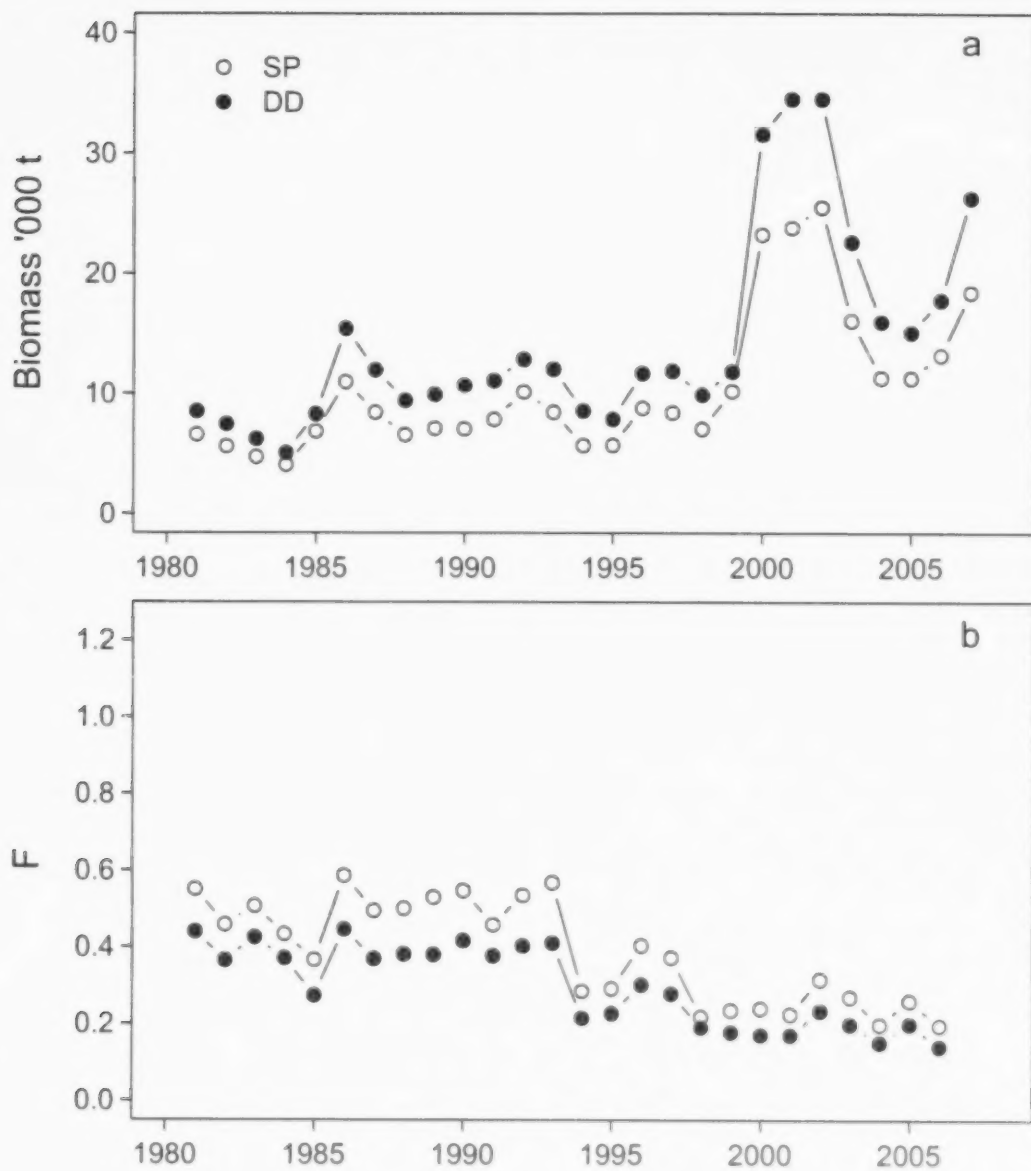


**Figure 27.** Residual plots for the default implementation of the delay-difference model (a), a delay-difference model with Gamma priors on variance terms (b), and a delay-difference model with Uniform priors on variance terms (c).

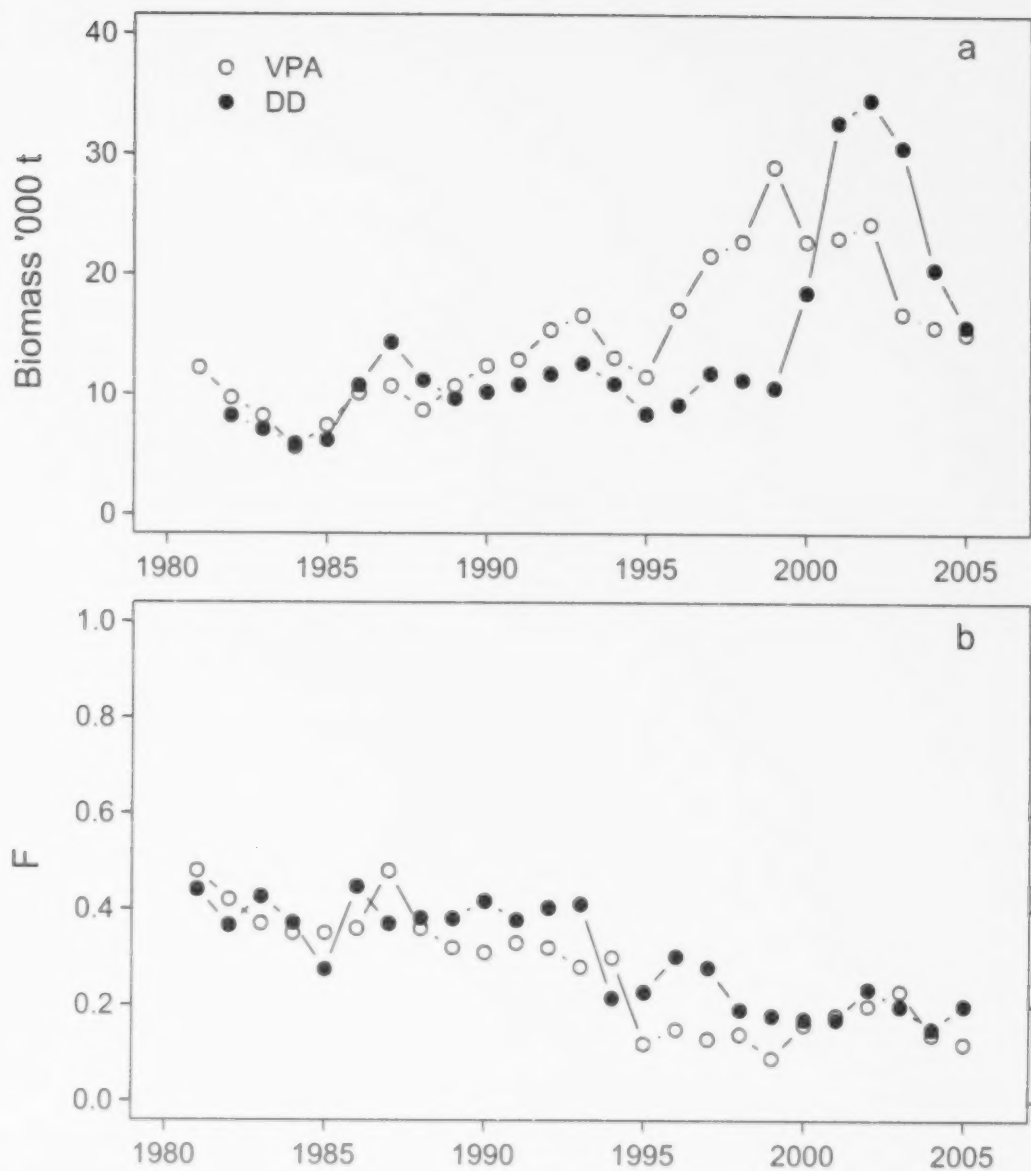


**Figure 28.** Fit of model estimates to observed data for the default implementation of the delay-difference model (a), a delay-difference model with Gamma priors on variance terms (b), and a delay-difference model with Uniform priors on variance terms (c).

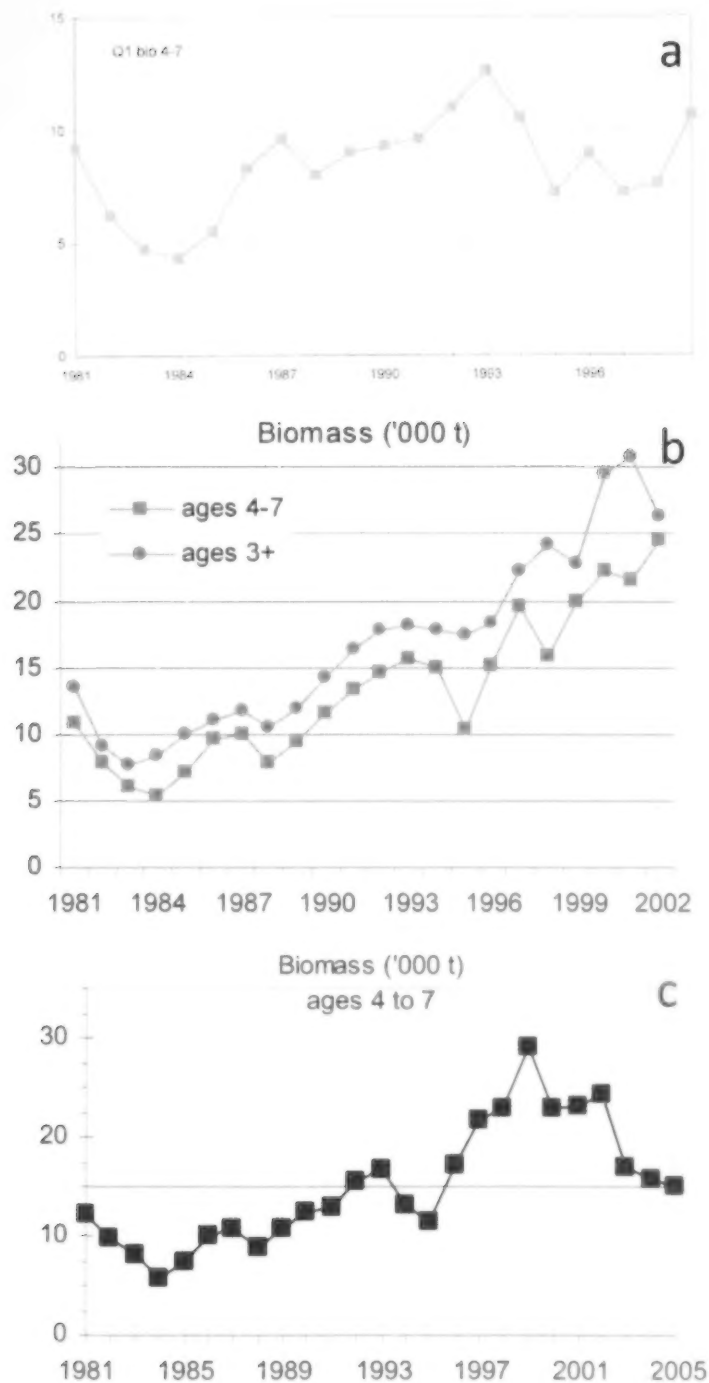




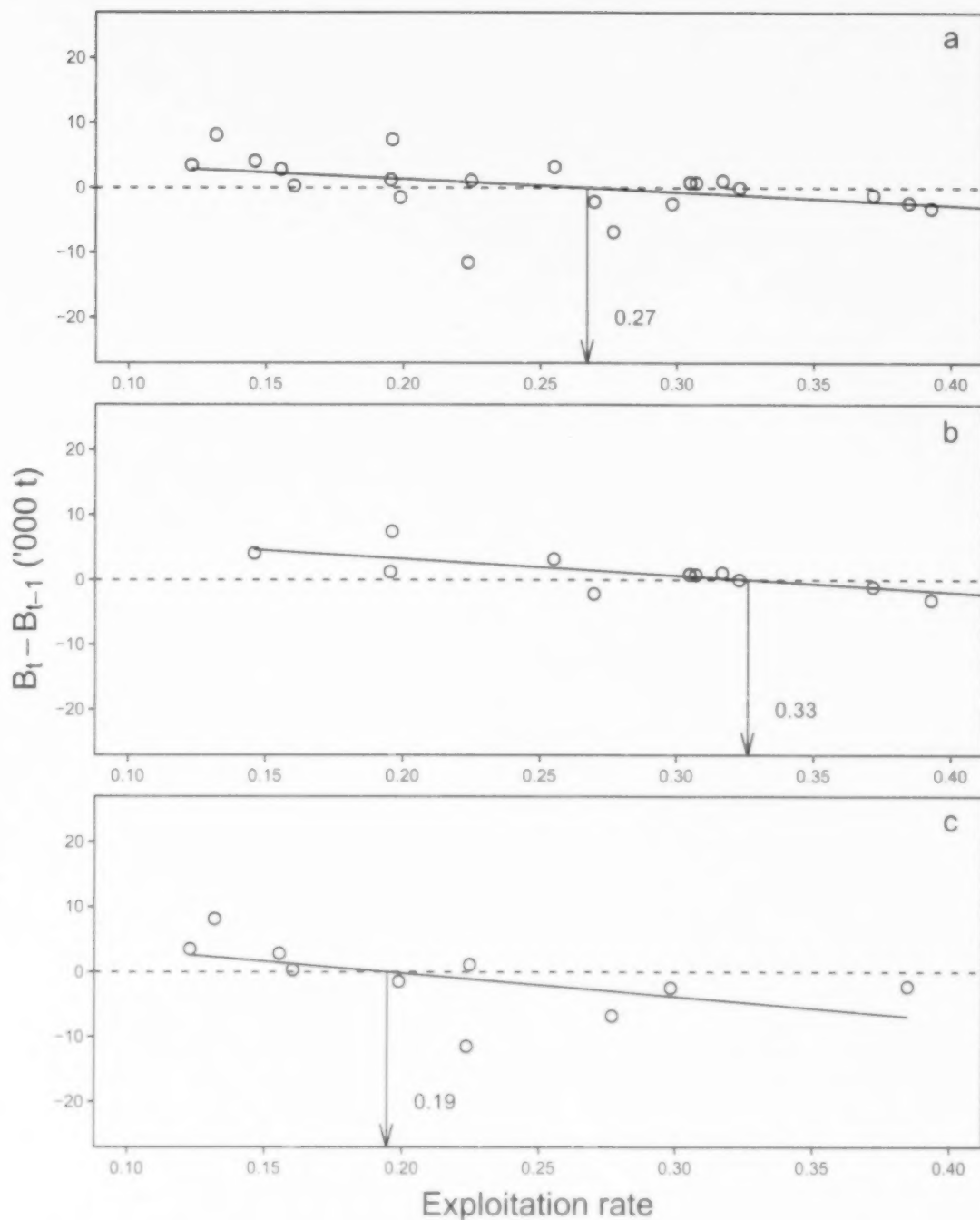
**Figure 29.** Comparison of biomass (a) and fishing mortality (b) estimates from the delay-difference model (DD) and the surplus production model (SP).



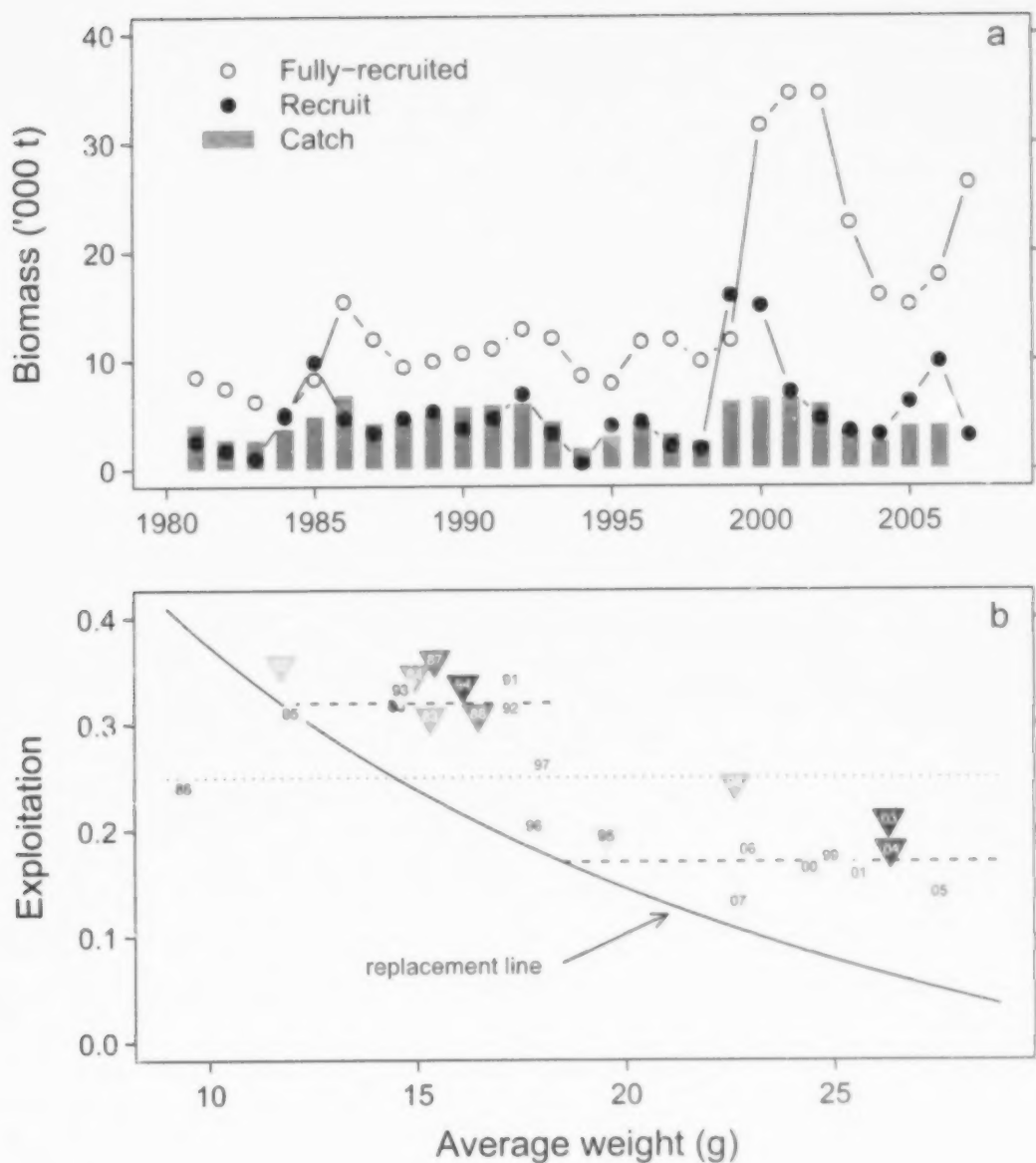
**Figure 30.** Comparison of biomass (a) and fishing mortality (b) estimates from the delay-difference model (DD) and the ADAPT VPA (VPA). DD estimates are for fully-recruited scallops, ADAPT VPA estimates are for age 4-7 scallops. Biomass estimates from the delay-difference model are adjusted to the start of the fishing season (Jan 1) to be comparable with ADAPT VPA estimates.



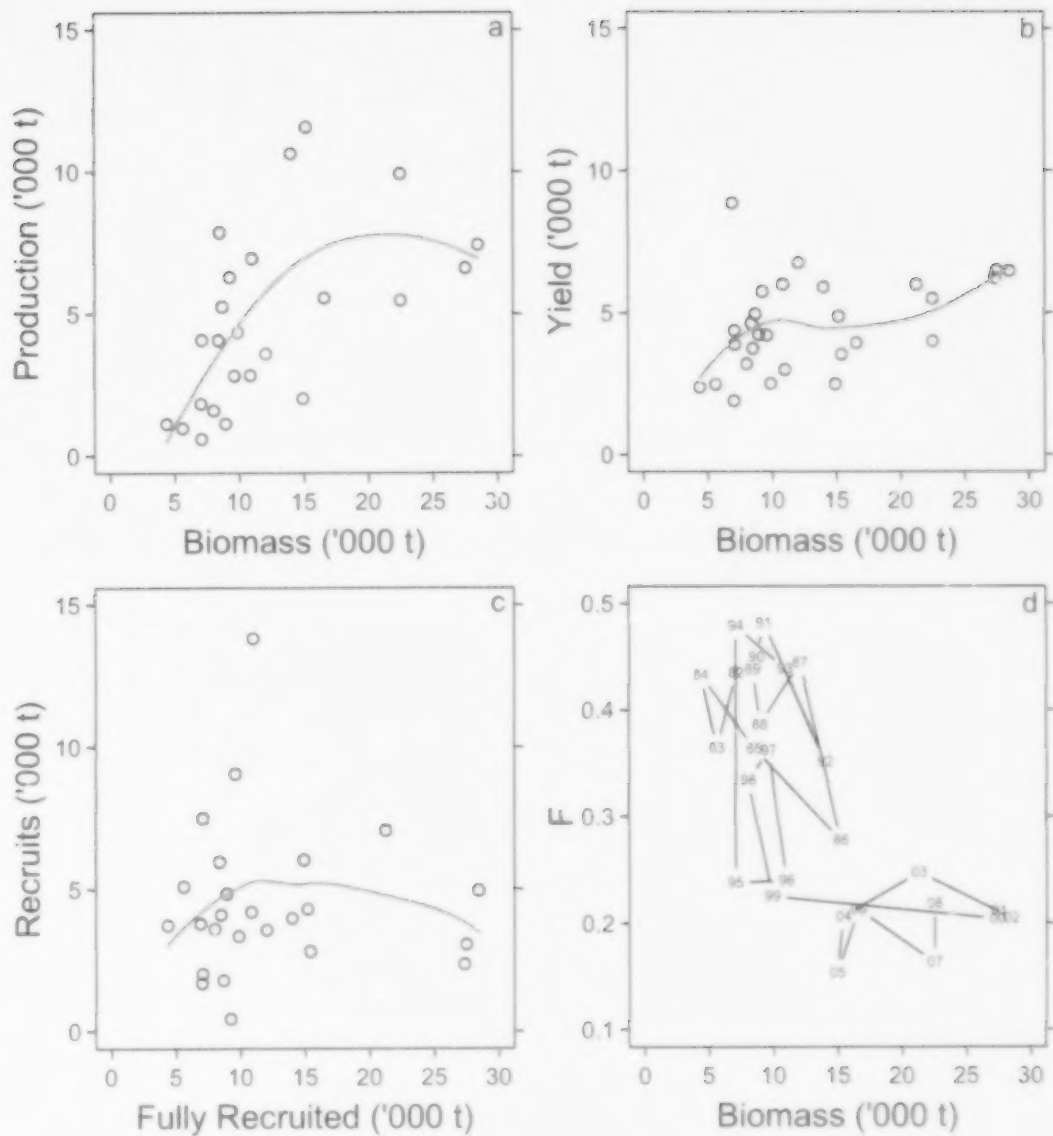
**Figure 31.** Trends in age 4-7 scallop biomass estimates from (a) the 1999, (b) the 2002 and (c) the 2005 Georges Bank scallop stock assessments. Biomass was estimated with the ADAPT VPA model. Figures a-c are reproduced from (Robert et al. 2000), (DFO 2003) and (DFO 2006), respectively.



**Figure 32.** Change in estimated biomass (fully-recruited) versus exploitation rate for three time periods, corresponding to different phases of stock size structure (indexed by average meat weight); (a) 1981-2007, (b) 1981-1996, excluding 1994, and (c) 1997-2007, including 1994. Exploitation reference points, i.e. the exploitation rate that results in no change in biomass, are indicated by the vertical arrows in each panel. Note, that the large biomass increase from 1999 to 2000 (●) was not included in linear regressions in panels (a) and (c).



**Figure 33.** Estimated trends in fully-recruited and recruit biomass with commercial catch (a). Exploitation rate versus average meat weight of fully-recruited scallops (b). The replacement line indicates the exploitation rate required to balance removals by the fishery with growth discounted for natural mortality. Orientation of triangles indicates direction of biomass change, shading is proportional to the magnitude of biomass change (ie. darker indicates a greater biomass change). Blue and green hues provide contrast between increases and decreases. Biomass increases occurring when exploitation was greater than the replacement line are possible when gains due to recruitment and growth are greater than losses due to natural and fishing mortality. Fixed exploitation reference points, see Figure 32, of 0.25 (1981-2007), 0.32 (1981-1996) and 0.17 (1997-2006) are displayed with horizontal dashed lines.



**Figure 34.** Production (a), Yield (b), Spawner-Recruit (c) and fishery phase (d) plots. The red lines in panels a-c are nonparametric loess smooths through the data with a span of 0.9.

## Appendix A

WinBUGS code for delay-difference population model.

```
delay-difference biomass dynamics
{
  # Priors
  logK ~ dnorm(9.21034, 3.418)
  K <- exp(logK)

  # priors for survey recruitment index
  for(t in 1:T){
    r[t] ~ dlnorm(0, 1)
  }

  # priors for catchabilities
  q1 ~ dunif(0, 1)
  q2 ~ dunif(0, 1)
  q3 ~ dunif(0, 1)
  qU ~ dunif(0, 1)

  # prior for process noise
  isigma2 ~ dgamma(3, 0.44629)
  sigma <- pow(isigma2, -0.5)

  # priors for observation errors
  # Survey biomass
  itau2 ~ dgamma(3, 0.44629)
  tau <- pow(itau2, -0.5)

  # Survey recruitment
  iepson2 ~ dgamma(3, 0.44629)
  epsilon <- pow(iepsilon2, -0.5)

  # Commercial catch rate
  inu2 ~ dgamma(3, 0.44629)
  nu <- pow(inu2, -0.5)

  # State equation
  Pmed[1] ~ dnorm(0, 0.000001)
  P[1] ~ dlnorm(Pmed[1], isigma2)

  for(t in 2:T){
    Pmed[t] <- log(max(exp(-m) * (rho + alpha / w.bar[t-1]) *
      (P[t-1] - C[t-1] / K) + exp(-m) * r[t-1], 0.001))
    P[t] ~ dlnorm(Pmed[t], isigma2)
  }
}
```



```

# Observation equations
for(t in 1:5){
  # Survey biomass
  Ifmed[t] <- log(q1 * K * P[t])
  If[t] ~ dlnorm(Ifmed[t], itau2)

  # Survey recruitment
  Irmed[t] <- log(q1 * K * r[t])
  Ir[t] ~ dlnorm(Irmed[t], ieppsilon2)

  # Output 1
  Ifpred[t] <- q1 * B[t]
  Irpred[t] <- q1 * R[t]
}

for(t in 6:15){
  # Survey biomass
  Ifmed[t] <- log(q2 * K * P[t])
  If[t] ~ dlnorm(Ifmed[t], itau2)

  # Survey recruitment
  Irmed[t] <- log(q2 * K * r[t])
  Ir[t] ~ dlnorm(Irmed[t], ieppsilon2)

  # Output 2
  Ifpred[t] <- q2 * B[t]
  Irpred[t] <- q2 * R[t]
}

for(t in 16:T){
  # Survey biomass
  Ifmed[t] <- log(q3 * K * P[t])
  If[t] ~ dlnorm(Ifmed[t], itau2)

  # Survey recruitment
  Irmed[t] <- log(q3 * K * r[t])
  Ir[t] ~ dlnorm(Irmed[t], ieppsilon2)

  # Output 3
  Ifpred[t] <- q3 * B[t]
  Irpred[t] <- q3 * R[t]
}

for(t in 1:T){
  # Commercial catch rate
  Umed[t] <- log(qU * K * P[t])
  U[t] ~ dlnorm(Umed[t], inu2)
}

```

```

}

# Output
for(t in 1:T){
  B[t] <- P[t] * K
  R[t] <- r[t] * K
  Upred[t] <- qU * B[t]
}
for(t in 2:T){
  mu[t] <- C[t-1]/(B[t]+C[t-1])
  Fmort[t] <- -log(max(1 - mu[t], 0.0001))
  Bs[t] <- (B[t] - B[t-1]) * 0.333 + B[t-1] # Jan 1 biomass
}

# Diagnostics
for(t in 1:T){
  Ifresid[t] <- log(If[t]) - Ifmed[t]
  Presid[t] <- log(P[t]) - Pmed[t]
  Irresid[t] <- log(Ir[t]) - Irmed[t]
  Uresid[t] <- log(U[t]) - Umed[t]

  sPresid[t] <- Presid[t] * 1/sigma
  sIfresid[t] <- Ifresid[t] * 1/tau
  sIrresid[t] <- Irresid[t] * 1/epsilon
  sUresid[t] <- Uresid[t] * 1/nu

  Ifrep[t] ~ dlnorm(Ifmed[t], itau2)
  pIsmaller[t] <- step(I[t] - Irep[t])

  Irrep[t] ~ dlnorm(Irmed[t], iepsilon2)
  pIrsmlaller[t] <- step(Ir[t] - Irrep[t])

  Urep[t] ~ dlnorm(Umed[t], inu2)
  pUsmaller[t] <- step(U[t] - Urep[t])
}

# Projections
for(i in 1:7){
  Pmed.p[i] <- log(max(exp(-m) * (rho + alpha / w.bar[T]) *
    (P[T] - C.p[i] / K) + exp(-m) * r[T], 0.001))
  P.p[i] ~ dlnorm(Pmed.p[i], isigma2)
  B.p[i] <- P.p[i] * K
  Bs.p[i] <- (B.p[i] - B[T]) * 0.333 + B[T] # Jan 1 biomass
  mu.p[i] <- C.p[i] / (B.p[i] + C.p[i])
  F.p[i] <- -log(max(1 - mu.p[i], 0.0001))
  pmu0.17[i] <- step(mu.p[i] - 0.17)
}
}

```

Initial values used to implement the delay-difference model.

```

inits <- list(list(logK = 8.2, q1 = 0.001, q2 = 0.001,
q3 = 0.001, qU = 0.001, isigma2 = 5, itau2 = 5, ieppsilon2 = 5,
inu2 = 5, P = c(0.5, 0.5, 0.5, 0.5, 0.5, 0.5, 0.5, 0.5, 0.5, 0.5,
0.5, 0.5, 0.5, 0.5, 0.5, 0.5, 0.5, 0.5, 0.5, 0.5, 0.5, 0.5,
0.5, 0.5, 0.5, 0.5), r = c(0.2, 0.2, 0.2, 0.2, 0.2, 0.2, 0.2, 0.2,
0.2, 0.2, 0.2, 0.2, 0.2, 0.2, 0.2, 0.2, 0.2, 0.2, 0.2, 0.2,
0.2, 0.2, 0.2, 0.2, 0.2, 0.2), Ifrep = c(1820.165, 1743.274,
1524.042, 1021.859, 3482.374, 9210.600, 4851.262,
3821.284, 4371.830, 3233.193, 3699.172, 8645.149,
5162.934, 2076.862, 2724.486, 4735.877, 3270.512,
2417.995, 3416.865 12243.913 14570.248 12536.142,
9492.819, 5486.862, 6117.094, 6775.394, 7545.411),
Irrep = c(602.2579, 388.8035, 201.4103, 929.3827,
2430.8372, 1977.5361, 1356.9730, 1898.3348, 2163.8986,
1317.6061, 1648.5035, 3173.6576, 1392.9583, 158.2391,
1403.7696, 1559.5001, 698.2977, 562.0891, 4786.0620,
6489.8581, 2705.3792, 1740.5733, 1255.7296, 1083.2348,
2286.6231, 3710.3593, 1001.1475), Urep = c(9.194921,
6.518953, 4.413197, 3.222573, 4.268247, 11.368103,
10.152357, 5.776547, 6.915492, 8.192404, 9.425944,
9.062385, 10.622878, 8.279333, 5.513937, 10.212459,
12.915733, 7.976340, 10.454184, 36.529386, 21.147024,
36.592507, 14.747600, 10.138207, 9.237438, 11.974399,
26.694000)), list(logK = 9.1, q1 = 0.2, q2 = 0.2, q3 = 0.2,
qU = 0.0001, isigma2 = 7, itau2 = 7, ieppsilon2 = 7, inu2 = 7,
P = c(0.1, 0.1, 0.1, 0.1, 0.1, 0.1, 0.1, 0.1, 0.1, 0.1, 0.1, 0.1,
0.1, 0.1, 0.1, 0.1, 0.1, 0.1, 0.1, 0.1, 0.1, 0.1, 0.1, 0.1,
0.1), r = c(0.9, 0.9, 0.9, 0.9, 0.9, 0.9, 0.9, 0.9, 0.9, 0.9, 0.9,
0.9, 0.9, 0.9, 0.9, 0.9, 0.9, 0.9, 0.9, 0.9, 0.9, 0.9, 0.9,
0.9, 0.9, 0.9), Ifrep = c(1820.165, 1743.274, 1524.042,
1021.859, 3482.374, 9210.600, 4851.262, 3821.284,
4371.830, 3233.193, 3699.172, 8645.149, 5162.934,
2076.862, 2724.486, 4735.877, 3270.512, 2417.995,
3416.865 12243.913 14570.248 12536.142, 9492.819,
5486.862, 6117.094, 6775.394, 7545.411), Irrep = c(602.2579,
388.8035, 201.4103, 929.3827, 2430.8372, 1977.5361,
1356.9730, 1898.3348, 2163.8986, 1317.6061, 1648.5035,
3173.6576, 1392.9583, 158.2391, 1403.7696, 1559.5001,
698.2977, 562.0891, 4786.0620, 6489.8581, 2705.3792,
1740.5733, 1255.7296, 1083.2348, 2286.6231, 3710.3593,
1001.1475), Urep = c(9.194921, 6.518953, 4.413197,
3.222573, 4.268247, 11.368103, 10.152357, 5.776547,
6.915492, 8.192404, 9.425944, 9.062385, 10.622878,
8.279333, 5.513937, 10.212459, 12.915733, 7.976340,
10.454184, 36.529386, 21.147024, 36.592507, 14.747600,
10.138207, 9.237438 11.974399, 26.694000))

```

# Data used to implement the delay-difference model.

```
data <- list(alpha = 9.47339, rho = 0.8189698, w.bar = c(11.731296,
15.325448, 14.966345, 11.963515, 9.379463, 15.445798, 16.481940,
14.495594, 14.540676, 17.263354, 17.259848, 14.614310,
16.115886, 19.533566, 17.807214, 17.995091, 22.627553,
24.914813, 24.410055, 25.595251, 22.749537, 26.304516,
26.358919, 27.504842, 22.928808, 22.698051, 25.204646),
T = 27, If = c(1820.165, 1743.274, 1524.042, 1021.859, 3482.374,
9210.600, 4851.262, 3821.284, 4371.830, 3233.193, 3699.172,
8645.149, 5162.934, 2076.862, 2724.486, 4735.877, 3270.512,
2417.995, 3416.865, 12243.913, 14570.248, 12536.142, 9492.819,
5486.862, 6117.094, 6775.394, 7545.411), Ir = c(602.2579,
388.8035, 201.4103, 929.3827, 2430.8372, 1977.5361, 1356.9730,
1898.3348, 2163.8986, 1317.6061, 1648.5035, 3173.6576, 1392.9583,
158.2391, 1403.7696, 1559.5001, 698.2977, 562.0891, 4786.0620,
6489.8581, 2705.3792, 1740.5733, 1255.7296, 1083.2348, 2286.6231,
3710.3593, 1001.1475), U = c(9.194921, 6.518953, 4.413197, 3.222573,
4.268247, 11.368103, 10.152357, 5.776547, 6.915492, 8.192404,
9.425944, 9.062385, 10.622878, 8.279333,
5.513937, 10.212459, 12.915733, 7.976340, 10.454184, 36.529386,
21.147024, 36.592507, 14.747600, 10.138207, 9.237438, 11.974399,
26.694000), C = c(4149.542, 2766.276, 2702.565, 3741.115, 4876.538,
6758.312, 4227.417, 4632.013, 4948.745, 5737.487, 5902.892, 5988.348,
4363.525, 1894.131, 2990.578, 4203.054, 3194.124, 2498.745,
6180.699, 6469.606, 6456.644, 5984.627, 3523.941, 2481.882, 3931.827,
4000.519), C.p = c(3500, 4000, 4500, 5000, 5500, 6000, 6500), m = 0.1)
```